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Janne Gress Sørensen

PhD Thesis

Department of Civil Engineering
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Preface

This thesis is submitted as a partial fulfilment of the Danish degree of Doctor of philosophy at the Technical University of Denmark (DTU). The project is carried out at the Department of Civil Engineering, Section of Building Design under supervision of Associate Professor, Anne S. Dederichs.

The project was initiated in October 2011 under the scope of the KESØ project, which was a joint research collaboration between DTU and Lund University in Sweden. The aim of the project was to strengthen fire safety research across Øresund.

The work is now about to end and so is my time at the university. After eight educational years I think, it is about the time to leave university and move on to see what is on the other side. I will however definitely maintain my connections to the university. Partly because my time at the university have taught me to be fond of teaching and because there, in my opinion, is still a lot of work to be done in order to ensure equal safety for everyone.

Kgs. Lyngby, September 30$^{\mathrm{th}}$, 2014

Janne Gress Sørensen

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Acknowledgement

Many people have contributed either directly or indirectly to this study, and I am very thankful for their effort.

First and foremost, I would like to give a special thank my supervisor associate professor Anne Dederichs, who encouraged and motivated me to start this PhD Study. Throughout the project you have given me valuable feedback and we have had very productive discussions. You have also given me a lot of freedom to form the project in the way i wanted.

The PhD study is conducted under the scope of the KESØ projekct. Thanks to Interrreg IV A ÖKS under the European Union for funding the KESØ project. I am also grateful for financial support from the Danish foundation Østifter, which enable me to have an external research stay in Boston, United States and conduct a series of experiments in Washington D.C..

Evacation experiments without participants would not give any results. I would therefore also like to thank a number of people, who assisted me in the recruitment process of participants and who provided experimental facilities. Thanks to John Gudmand, John Heilbrunn and Betina Pedersen for your assistance with my experiments in Denmark and Marsha Mazz for the help with the experiments conducted in Washington D.C..

Thanks to the National Fire Protection Association for hosting me during my external research stay. In addition, thanks to Robert Solomon for your huge work related to my experiments, Rita Fahy for taking care of me and ensure everything was running as planed, and lastly Allan Fraser for valuable discussions about fire safety for people with disabilities and technical assistance.

Another thanks go to my colleagues at Department of Civil Engineering, espacially the fire safety group and PhD colleagues for professional discussions and feedback. A special thanks go to my two friend and former PhD colleagues, Aldis Run Larusdottir and Annemarie Poulsen, with whom I have shared office. I appreciate our professional discussions and you have given me valuable feedback.

And most importantly my family and friends, without your support and encouragement it would have been a hard time to complete the study. Especially a grateful thanks to Martin Frederiksen, you were there for me at all times and helped me through the hard and busy times. Also a thank to my parents, you have interestingly followed my project and even participated in some of the experiments.

Thank you all!

Abstract

Fire has always been a threat to human beings and claims lives every year. A lot is done to ensure fire safety in our buildings and structures, but fires still occur and lives are lost. In the past decades there has been a trend towards more and more complex buildings, which challenge fire safety engineers and the prescriptive fire safety codes. Consequently, performance based fire codes have been developed and implemented in countries around the world. Performance based codes allow for use of engineering tools and calculations. Meanwhile, accessibility to the building environment has likewise gained an increased focus in the past decades enabling everyone to enter buildings but is not an insurance for egressibility. Representative evacuation data for vulnerable subpopulations, including elderly, children and people with disabilities, are lacking in literature. It is known that the fatality rate caused by fire for this segment of the population is larger than for able-bodied people. It can therefore be questioned whether our buildings provide a sufficient safety level for this group of people.

The aim of the PhD Study is to increase knowledge and data on evacuation characteristics of vulnerable people and with a special focus on blind and visually impaired people. An experimental program was designed to obtain data on walking speeds horizontally and descending stairs, interaction between participants and their interaction with the building environment. Experiments were conducted in different buildings including office buildings, an institutional building and a tunnel. In total 148 people have participated in the experiments. Parallel to the evacuation experiments participants were interviewed not only about their experience with the experiments but also their use of different building types and the difficulties they meet.

The interview study revealed that people with disabilities visit all kind of buildings. It is therefore not possible to neglect their presence in buildings while ensuring equal egress for all occupants. It was also found that building elements

such as stairs, signage, doors e.t.c, which are essential elements for a safe and easy evacuation, challenge the movement for occupants having an impairment.

Quantitative results on reaction times, walking speeds horizontally and descending stairs were also obtained from the experiments. The theoretical Nelson and MacLennan describing the relation between movement speed and person density was used for comparison. It was found that the Nelson and MacLennan model (N&M model) correlates with results found for able-bodied. This is expected since the model is based on data for this group. Likewise, the theoretical model is a conservative estimate for the hearing impaired participants descending stairs and for children and cognitive impaired participants moving on horizontal planes. For all tested subpopulations the walking speed decreased with increasing person density, but the visually impaired participants are least affected and could maintain a higher walking speed for a longer time. A correlation was found between the reaction time and how close people are seated. A correlation between reaction time and subpopulation could not be documented.

Observations made during the experiments showed that participant generally behaved altruistically and assisted fellow participants to evacuate. There are examples of elderly people guiding and assisting children to evacuate, deaf people assisting mobility impaired people, and able-bodied individuals who lend a helping hand to a blind participant and guide him to the place of safety.

The heterogeneity of the test sample is also investigated. Comparing the total egress time for a heterogenous test population with a homogenous test population only comprising able-bodied adults it was found that it took twice the time to evacuate the heterogenous group. This result clearly demonstrates that the composition of occupants and their respective evacuation characteristics highly influence the evacuation flow. Hence, precautions should be taken while selecting the occupant distribution for fire safety calculations.

Resumé

Brand har altid været en trussel mod mennesker og forårsager hvert år tab af menneskeliv. Der er foretaget mange tiltag for at brandsikre vores bygningsværker, men brand opstår stadig og koster menneskeliv. Gennem de seneste årtier er der opstået en tendens til at bygninger opføreres mere og mere komplekst. Dette udfordrer brandingeniørerne og de præskriptive brandkrav. En konsekvens heraf er udvikling og implementering af de funktionsbaserede brandkrav. Samtidig er tilgængelighed til bygninger også blevet et krav, som dermed muliggøre at alle uanset funktionsnedsættelse kan komme ind i en bygning. Tilgængelighed er dog ikke en garanti for at man også kan komme ud i tilfælde af eksempelvis brand. Repræsentative evakueringsdata for de udsatte grupper er stærkt begrænset. Studier har ligeledes vist at raten af branddøde er større for de udsatte grupper sammenlignet med voksne uden funktionsnedsættelser. Det er derfor spørgsmålet om brandsikkerheden i vores bygninger er tilstrækkelig for denne gruppe af mennesker.

Formålet med dette PhD studium er at øge viden og data om de udsatte gruppers evakueringskarakteristik. Der er samtidig et særligt fokus på blinde og svagsynede. Der er udviklet et forsøgsprogram til indsamling af data for ganghastigheder vandret og ned ad trapper samt interaktion mellem deltagere og deres interaktion med selve bygningen. Forsøgsprogrammet involverede 148 forsøgspersoner. Parallelt med evakueringsforsøgene blev deltagerne interviewet omkring deres oplevelse af evakueringsforsøgene, samt deres brug af forskellige bygningstyper i deres dagligdag og de udfordringer de møder.

Resultatet af interviewundersøgelserne viste at personer med funktionsnedsættelser besøger alle typer bygninger. Det er derfor ikke muligt at negligere deres tilstedeværelse i bygninger, og deres flugtmuligheder skal ligeledes sikres på lige fod med alle andre. Bygningselementer såsom trapper, skiltning og døre viste sig at give udfordringer for personer med funktionsnedsættelser. Ligeledes er disse elementer vigtige komponenter i en flugtvej.

Kvantitative resultater for reaktionstider, ganghastigheder på vandrette planer og ned ad trapper blev indsamlet via evakueringsforsøgene. Det viste sig, den teoretiske N&M model korrelerede med resultaterne for voksne uden funktionsnedsættelser. Dette var forventet, idet denne model er udviklet på baggrund af data for denne gruppe mennesker. Den teoretiske model gav ligeledes et konservativt estimat for ganghastigheder vandret for hørehæmmede samt for børn og personer med kognitive funktionsnedsættelser ved gang ned ad trapper. Det viste sig endvidere at ganghastigheden faldt ved stigende persondensitet for alle de testede sub-populationer. Gruppen af blinde og svagsynede var dog mindst påvirkede at den omgivende persondensitet og kunne opretholde en højere ganghastighed selv ved stigende densitet. Der blev fundet en korrelation mellem reaktionstiden og hvor tæt deltagerne sad på hinanden. Der blev ikke fundet nogen korrelation mellem reaktionstid og sub-population.

Observationer foretaget under evakueringsforsøgene viste at deltagerne generelt udviste altruistisk adfærd og hjalp hinanden. Der er eksempler på ældre der guider og hjælper børn ud, døve som hjælper personer med reduceret mobilitet, og personer uden funktionsnedsættelser der giver en hånd til en blind og guider ham til det sikre sted.

Betydningen af heterogeniteten afspejlet i gruppen af forsøgspersoner blev undersøgt. En sammenligning af de totale evakueringstider viste, at det tog dobbelt så lang tid for den heterogene gruppe at bringe sig i sikkerhed, som det tog for den homogene gruppe med voksne uden funktionsnedsættelser. Dette resultat viser med al tydelighed at sammensætningen af personer og deres respektive evakueringskarakteristik har en stor indflydelse på evakueringsflowet og den totale evakueringstid. Det er derfor vigtigt at udvælge fordelingen af persontyper i en bygning under hensyntagen til dette.

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C. Kindler, J.G. Sørensen and A.S. Dederichs, Evacuation of mixed populations from trains on bridges. 2012, In Proceedings: 6th International Conference on Bridge Maintenance, Safety and Management.

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Validation of evacuation model using real data - what is the influence of the composition of the population?. 2013, In Proceedings: 13th International Conference and Exhibition on Fire Science and Engineering.

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Chapter 1

Introduction

Fire has always been and will always be associated with danger. Each year people lose their lives due to fire and the consequences thereof. Meanwhile we spend the majority of our lives inside buildings and therefore wish them, to be safe and protect us from hazards. Safety of buildings is likewise important for life quality [1,2], since an unsafe environment can lead to stress, [3]. To enhance and uphold a good quality of life, safety design of our buildings needs to take into account the characteristics of the building occupants including people with disabilities. Buildings build within the last couple of decades turn out more and more complex. Engineers nowadays therefore face big challenges designing spectacular and often complex buildings and at the same time ensuring that the same building is safe and can protect occupants.

1.1 Fire Safety Design Codes

Traditionally, fire safety has been addressed through the application of fire safety codes, the so-called prescriptive codes. The prescriptive codes, which are often set after sequences of real fires, [4], give requirements on e.g. maximum distance to nearest exit, width of exits and number of exits etc. These requirements limit the architectural freedom and lead to the establishment of traditional buildings, divided into sections and subsections. According to prescriptive codes buildings are divided into categories dependent on occupant characteristics. There is made a distinction between daytime and nighttime use, familiarity with the building and whether occupants are able to evacuate unassisted. People with impairments (temporary or permanent), children and elderly people are often categorised based on a need for assistance during evacuation, [5]. Thus, leaving this group of people to one single building category even though they might be present in various categories.

The increased complexity of buildings that have erected in the past decades has implied an increased demand for flexible regulations regarding building design, including the fire safety design. As a consequence engineers face difficulties in fulfilling prescriptive requirements for the fire safety. In many countries around the world, the prescriptive codes have therefore been replaced by performance based codes. The process of replacement started in Europe in 1975 with Iceland introducing performance based codes, followed in 1985 by England, 1994 by Sweden and Belgium, 1997 by Norway and Finland, 2005 by Scotland, 2006 by Spain and 2007 by Italy [6]. In Denmark the performance based codes were introduced in 2004. Implementation of the performance based codes allow fire safety engineers to use engineering tools e.g. simulation and tests, to verify that a buildings safety level is sufficient instead of fulfilling requirements prescribed by the code. Furthermore, performance based codes give the possibility to design a building in a more innovative and sustainable way.

Assessment of the personal safety level in a building can be made by comparing the required safe egress time (RSET) with the available safe egress time (ASET) and then add a safety margin, see figure 1.1. The two terms RSET and ASET is relatively self-explanatory. RSET is the time needed for everybody to reach a place of safety, consisting of contributions from warning time (t_w), reaction and decision time (t_{rd}) and movement time (t_m). ASET is the time until critical and life threatening conditions occur. Fire modelling can be used to compute the time until critical conditions occur. The input for these calculations are parameters characterising the chosen design fire and the building geometry. Thus, ASET is based on fire dynamics and chemistry. Contrary, RSET is based on evacuation models. The evacuation models used to predict RSET is based on the occupants evacuation characteristics e.g. walking speed and human behavior. In complex buildings evacuation simulation software is used to make prediction of the total evacuation time and most of the software solutions offer the possibility to assign different walking speeds to different groups of people within the modelled building. However, the majority of data available are collected more than 30 years ago and are often based on able-bodied adults. Consequently, there is a lack of data describing people with impairments as well as elderly people and children, [7–9]. These segments of the populations is deemed to be more vulnerable in emergency and fire incidents. Studies conducted in the United States, Denmark, Scotland, New Zealand and Japan have shown that the fatality rate for members of the vulnerable part of the population is higher compared to able-bodied individuals, [10–18]. Given a higher fatality rate for the vulnerable segment of our population raises the question; "Are the fire safety level in buildings sufficient for the vulnerable segment of our population?".

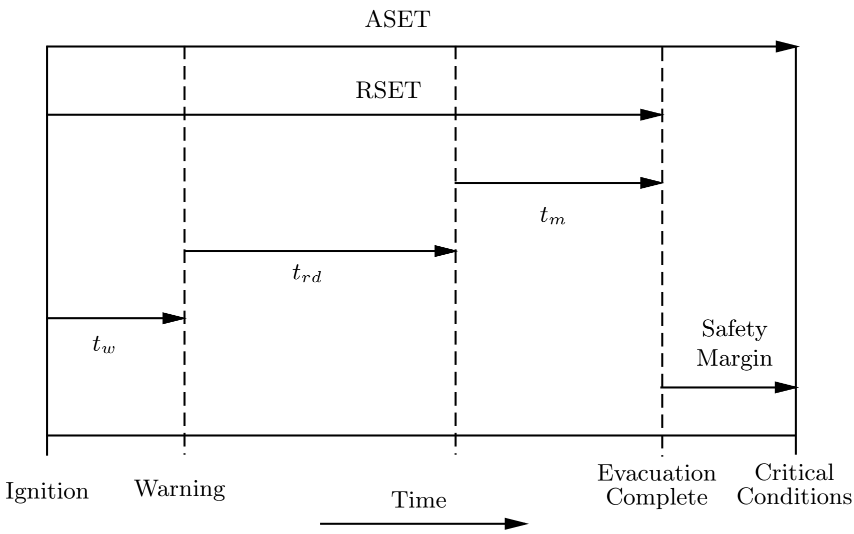

Figure 1.1: Egress time model. With inspiration from [19] and [20].

1.2 Accessibility, Egressibility and Human Rights

In the past decades the focus on human and civil rights for people with disabilities has increased. Nevertheless, human rights for people with disabilities is not a new phenomena and can be dated back to 539 B.C with the persian King Cyrus' declarations of tolerance, justice and religious freedom, [21]. But, it was not until 1948 that these rights were codified into a single document, The Universal Declaration of Human Rights (UDHR), [22, 23]. This document became more commonly accepted and powerful, and all member states of United Nations have ratified at least one of the nine human right treaties, [24]. The UDHR prescribes universality, interdependence and indivisibility, equality and non-discrimination. In 1990 the first initiative for specific human rights for people with disabilities was undertaken by United States of America and one of the most comprehensive pieces of legislations was signed into law (Americans with Disabilities Act - ADA). The United Nations adopted the Convention on the Rights of People with Disabilities in 2006, explicitly stating rights for people with disabilities, [25]. The question is then how to practically ensure that people with disabilities are not discriminated and are treated on equal terms as non-disabled people.

Accessibility to buildings is one way of establish equal possibilities for all people independent of their (dis-)abilities and is in many countries a part of the legislation [5, 26–29]. The requirement of accessibility likewise applies to urban environments, [5,26,30]. The increased accessibility to buildings and urban environments might consequently lead to a large representation of people with disabilities in these areas. An indicator that confirms an increased presence of disabled people in buildings is that the employment rate of this particular group of people has increased within Europe [31, 32]. Accessible buildings is furthermore a contributing factor to increased social quality which is used as an evaluation parameter for sustainable building design solutions [33]. Considering all building occupants and giving them equal possibilities to apply the functionality of the building contributes to the social quality of the design. Transforming social quality to fire safety design entail enabling equal egressibility. Hence, circumvent that the building design disable parts of the population excluding them from self-evacuation, and leaving them to be rescued by the rescue service.

Accessibility and egressibility is in some cases contradictory. Take for example a high-rise building; To reach the upper floor the elevator is used, but during fire use of elevators is generally not allowed (in some buildings fire fighter elevators are installed and might be used for assisted evacuation). Then, how do you get out off a burning building if you are bounded to a wheelchair?. Hence, accessibility do not automatically lead to egressibility. From an evacuation point of view there is a lack of understanding and knowledge on the evacuation characteristics and capabilities of people with disabilities, and literature only provide limited information on evacuation and evacuation characteristics for the more vulnerable segments of our population.

1.3 Evacuation Data on Vulnerable People

Statistics show that 10-20% of the population, worldwide, have some kind of disability [34–36]. In addition, studies have revealed that the prevalence of people with disabilities increases with age and with an increasing ageing population a large proportion of the future building occupants will presumably have some kind of disability [37–39]. Furthermore, it is estimated that 26.3 % of the worlds population is aged 0-14 years, [40]. Previous studies have demonstrated that people aged younger than 12 years can be considered as children from a fire safety perspective [41]. Comparing characteristics essential for fire safety and evacuation, such as walking speed and behavior, it is assumed that children, elderly people and people with disabilities constitute a vulnerable population. Hence, the characteristics of this group is different from able-bodied people. The group of people with disabilities is broad and do not only comprise people with permanent impairments, but also temporary impairments. Examples of temporary impairments that influence evacuation characteristics and restrict evacuation performance are; pregnancy, broken bones, obesity, effects related to alcohol and/or drug intake. Hence, the vulnerable segment of our population worldwide constitute a considerable proportion and can therefore not be neglected when evaluating fire safety in buildings and society.

The vulnerable segment of our population generally have a normal and independent life and integration of the disabled people in society has increased in recent years [30]. Studies conducted in Northern Ireland and UK revealed that a large proportion of people with disabilities goes out, thus taking part in activities outside their home [42]. Another indicating factor that contributes to a larger prevalence of vulnerable people, outside their homes, is a general increase in employment policies and initiatives to increase job possibilities and inclusion of people with disabilities, [43]. It must consequently be assumed that vulnerable people are present in various building types besides residential buildings.

The fire fatality rates for members of the vulnerable segment of the population have been shown to be larger than for able-bodied people, [10–13]. Hence, there is potential for decreasing the fire fatality rate for vulnerable people by focusing on the fire evacuation characteristics of this group of people. However, people with disabilities are more likely to be excluded from fire evacuation drills or left behind because they need assistance to evacuate, for ethical reasons or to reduce potential injury. Consequently, there is a lack of available information about vulnerable people and their characteristics during an evacuation. Literature provide limited knowledge and data on evacuation of different segments of the vulnerable population.

The available literature describing evacuation characteristics of vulnerable people include studies of elderly and children as well as people with reduced mobility, hearing, and vision and people with cognitive impairments. Hence, covering a substantial proportion of the vulnerable segment. However, the studies are broader and have a limited number of test subjects compared to the large amount of data available on able-bodied people.

Information and evacuation characteristics for the elderly segment of the population is primarily collected via evacuation drills in residential buildings and housing facilities for elderly people, [44–47]. Generally, elderly people have a reduced walking speed compared to able-bodied people adults. Furthermore, elderly people might have an impairments that likewise will affect their evacuation performance.

The group of people with reduced mobility comprises a large variation, but in general they need some kind of movement aid to get from one point to another. Some might need an artificial limb, others one or two crutches and again others use a wheelchair (manual or electric). The large variation is also reflected in the data found in literature. Boyce et al. conducted a major study, in the late nineties investigating evacuation characteristics of disabled people [48]. This study provided valuable input parameters for designers and modelers. A similar study conducted in Sweden aimed at identifying and quantify factors that influence the evacuation capability of people with different locomotion disabilities [49]. Results revealed that the horizontal walking speed varied from 0.6 m/s and up to 2.5 m/s. Also in Russia, evacuation of mobility impaired people have been studied, [50]. Kuligowski et al. studied disabled peoples movement on stairs in high-rise evacuation and found that assisted occupants moved faster than unassisted disabled people [46]. Building occupants who use a wheelchair or are bedbounded generally cannot evacuate using stairs. Assistive evacuation devices for this segment of the population have therefor been developed. Adams and Galea conducted several experiments testing different evacuation assistive devices [51]. They found that the most efficient device was an evacuation chair. Other studies also investigated the performance of different evacuation devices [52], [53]. However, these devices required a handler(s) to be operated and that makes the disabled person highly dependent on assistance from others.

Different studies related to visually impaired individuals' performance during an evacuation are found in literature. In 1986 Clark-Carter et al. studied the preferred walking speed for visually impaired people under normal conditions for three different route designs, [54]. It was found that the walking speed decreased significantly as the complexity of the route increased. Even though the study assessed walking speeds in normal conditions, the reduced speed is relevant for fire safety and design of egress routes. The more complex the egress route, the more difficult it is to navigate through and the longer it takes to reach a place of safety. Two years later, in 1988, Passini and Proulx investigated way-finding abilities for blind and visually impaired people, [55]. They found that visually impaired people rely heavily on reference points along a pre-planned journey and that they plan the journey in more details than normal sighted people. Finally , the authors emphasized that due to increased accessibility to buildings it was about the time to increase awareness of safety requirements for this segment of the population and ensure safe public settings. In the late nineties studies focusing on walking speed of blind and visually impaired occupants were conducted, [48, 56]. Emergency lighting conditions influencing visually impaired peoples way-finding abilities were studied by Wright and Cook and Cook et al., [56, 57]. It was found that the walking speed of visually impaired people is 45% to 70% of those of normal sighted people walking horizontally and 75-80%

descending stairs. Recently, a study in Russia investigated evacuation flow of blind and visually impaired individuals, [58]. Experiments were conducted in both familiar and unfamiliar environments. It was found that people with visual impairments move considerable faster in a well-know environments compared to unknown environments.

Cognitive impairments cover a broad selection of people being mentally challenged. Given the diversity, it is difficult to precisely describe common evacuation characteristics for this group. The challenges cognitively impaired people face are often related to pre-movement activities such as perception of warning and reaction and decision times. A study by Shields et al. assessed the evacuation behavior of people with learning difficulties, [59]. The study revealed that training conducted for a daytime scenario could not be transferred directly to a nighttime scenario. Thus, indicating the importance of considering different scenarios while performing training of evacuation procedures. Furthermore, test subjects behaved differently compared to able-bodied adults and the social influence was found absent.

People suffering from deafness or hard hearing might not be challenged on their movement capabilities but rather in the pre-movement phase in the event of fire. Systems to warn people about fire and other emergencies are often based on audible information e.g. siren, and spoken warning message. This type of warning systems do not process accessible information to the hearing impaired segment of the population and their response will consequently be delayed. The visual alarm is not a new phenomena but has been used where silent alarms were required or where high noise levels occur such as in factory environments, [60]. Combining visual and audible alarm systems would ensure that both hearing and visually impaired individuals will be notified about an incident.

Evacuation characteristics describing children have gained more interest in recent years and information and data available have increased. Studies in Denmark, Russia, Spain, and Brazil have been among the major contributors [61–66]. A more thorough literature review is conducted by Larusdottir, [41].

An overview of the quantitative measures for walking speeds on the horizontal and descending stairs is displayed in table 1.1 and 1.2. The tables do not include the findings revealed from the present study, neither are finding related to movement on inclined surfaces taken into consideration. It is chosen to only include horizontal movement and descent of stairs, because these elements are common parts of an egress route.

Table 1.1: Literature for data on horizontal movement.

Year	Walking Speed, $[m/s]$	Sub. Pop.	Notes	Source
1986	1.6	Visual	Normal conditions, Preferred walking speed, Route complexity	Clark-Carter et al. [54]
1999	0.3-0.9	Visual	Emergency drill, Normal lighting	Wright et al. [56]
1999	0.80	Locomotion disability	Experiment, Various aid used	Boyce et al. [48]
	0.89	Electric wheelchair		
	0.69	Manual wheelchair		
	0.78	Assisted ambulant		
	1.30	Assisted wheelchair		
2001	0.6-1.4	Locomotion disability	Experiment	Brand et al. [49]
	0.32-2.4	Manual wheelchair		
	1.21-2.5	Electric wheelchair		
2010	0.9	Reduced mobility*	Drag Mattress (2)	Adams and Galea [51]
	1.1	Reduced mobility*	Stretcher (4)	
	1.5	Reduced mobility*	Carry+Chair (1+1)	
	1.5	Reduced mobility*	Evac+Chair (1+1)	
2012	0.7	Disabled wo aid	Experiment in Retirement house for elderly citizens	Kholshevnikov et al. [45]
	0.43	Disabled w aid		
	0.61	Elderly		
2013	1.03	Mobility wo aid	Hospital evacuation drill	Samoshin and Istratov [50]
	0.73	Mobility w 1 aid		
	0.92	Mobility w 2 aids		
	1	Wheelchair user		
	0.97	Mixed flow		
2014	0.83	Visual	Experiment Familiar route	Samoshin and Istratov [58]
	0.44	Visual	Unfamiliar route	

* Test of evacuation devices for persons with reduced mobility. Number of handlers needed to operate the device is given in brackets.

Table 1.2: Literature for data descending stairs.

Year	**Walking Speed,** $[m/s]$	**Sub. Pop.**	**Notes**	**Source**
1995	0.57-0.88	People with limitations	Drill Residential Building A, B, C	Proulx et al. [44]
	0.56-0.57	Elderly	Drill Residential Building B, C	
1999	0.6	Visual	Emergency drill, Normal lighting	Wright et al. [56]
1999	0.33	Locomotion disability	Experiment, Various aid used	Boyce et al. [48]
	0.11-0.23	Assisted ambulant		
2010	0.62	Reduced mobility*	Drag Mattress (2)	Adams and Galea [51]
	0.55	Reduced mobility*	Stretcher (4)	
	0.57	Reduced mobility*	Carry+Chair (3M/4F)	
	0.81	Reduced mobility*	Evac+Chair (1)	
2012	0.46-0.47	Disabled wo aid	Experiment in Retirement house for elderly citizens	Kholshevnikov et al. [45]
	0.2-0.29	Disabled w aid		
	0.38-0.42	Elderly		
2012	0.23	Cane user	High-Rise evacuation drill	Kuligowski et al. [46]
	0.25	Assisted occupant		
	0.18	Assisted by fire fighter		
	0.21	Stair Descent device		
	0.41	Elderly		
2013	0.7	Mobility wo aid	Hospital evacacuation drill	Samoshin and Istratov [50]
	0.4	Mobility w 1 aid		
	0.7	Mixed flow		
2014	0.67	Visual	Experiment Familiar route	Samoshin and Istratov [58]
	0.36	Visual	Unfamiliar route	

* Test of evacuation devices for persons with reduced mobility. Number of handlers needed to operate the device is given in brackets.

The field of fire safety and evacuation is still a relatively new research area, and the early studies within evacuation and pedestrian flow dynamics primarily focused on characteristics of able-bodied adults [7–9]. The majority of existing evacuation data available in literature therefore describe evacuation characteristics of able-bodied adults. These data were collected more than 30 years ago and with a different demographic profile than found today. However, it still creates the foundation for input to various evacuation models and is reproduced in different guidelines, [20,67–69]. None of the data are derived from real emergencies and the characteristics of the test subjects were able-bodied adults, mainly males. The studies conducted by Pauls originated from evacuation drills in tall office buildings in Canada whereas the results derived by Fruin came from transport terminals, [9], [7]. The latter study by Predtechenskii and Milinskii was performed in the Soviet Union during normal use of public buildings [8]. Results from the above mentioned work are combined into a model describing the relation between walking speed as a function of person density developed by Nelson and MacLennan, [67].

Evacuation characteristics describing homogeneous groups of people with different impairments cannot be applied directly in evacuation calculations. Certain characteristics might be influenced by other people in the evacuation flow. Studies of heterogeneous populations and mechanisms influencing the flow are therefore needed to obtain a more accurate and representative results. Studies assessing the social influence during the initial phase of an evacuation and the resulting human behavior is found in literature, [70–72]. Research specifically addressing the influence of occupant composition on quantitative measures are therefore needed.

The amount of data on able-bodied adults are predominant compared to other subpopulations. A reason to the predominance might be that able-bodied adults are easy to recruit in large number and from few places e.g. the military or university. Recruiting people from military and university can be done with little effort. In addition, ethical considerations and national ethical legislation might restrict researcher from conducting evacuation studies and exercises involving people with disabilities.

1.4 Research Objectives

The overall aim of the PhD study is to gain knowledge about and data on evacuation characteristics describing people with mixed abilities. Data are obtained through a program of evacuation experiments with varying composition of the test subjects. The study focuses partly on evacuation characteristics of heterogeneous groups representing the diversity of society, and partly on the characteristics describing blind and visually impaired people during an evacuation. It is expected that the findings will influence future guidelines and recommendation, to include a representative description of all segments of our population. The research objectives are formulated in a set of hypothesises.

- There is a large diversity of people in our society and the composition of building occupants reflect that. When designing buildings and their fire safety different occupants will influence the design of the egress system(s).
- People with impairments have different evacuation characteristics and behave differently compared to able-bodied people during an evacuation. It is therefore not possible to apply a normative theory representative for all segments of the population.
- Evacuation characteristics such as walking speed, flow and human behavior are different for mixed groups compared to homogenous groups of able-bodied people.
- Total evacuation times are affected by the characteristics of occupants.
- People with visual impairments have a lower walking speed compared to able-bodied people and have a different behavioral pattern.
- The degree of vision loss affects the evacuation characteristics of visually impaired people.

The hypotheses are tested throughout the PhD study and create the foundation for designing the experimental program.

1.5 Structure of Thesis

The present thesis is structured as a paper-based thesis as recommended by the PhD School at Department of Civil Engineering, Technical University of Denmark. The core of the thesis consist of three published or accepted peer-reviewed journal papers and one peer-reviewed conference paper. The four papers presented in chapter 3 to chapter 6 are a result of the research conducted throughout the PhD study. The papers selected for the thesis demonstrates the core part of the research activities carried out within the scope of the PhD study, but is not presented in chronological order. The order, in which the papers are presented, is determined based on the content, presenting evacuation data for heterogenous groups first and then further investigate a specific subpopulation (here visually impaired individuals). The four core papers are tied together by two additional chapters - Experimental Program and Summary of Findings (Chapter 2 and Chapter 7). These two chapters contain information about the experiments not described in papers and an overview of findings across the papers. Supplementary results and findings are available in appended conference papers, posters, abstracts and a scientific report. Experimental plans, questionnaire used in interview survey and informed consent forms are likewise appended.

Chapter 2 describes the full experimental program conducted throughout the PhD study. The chapter gives detailed descriptions of the test sample, test locations and how the experiments are arranged and organized. The chapter also include a description on how the data are processed and analysed. The details described in this chapter is supplementary to the information found in the core papers and is more comprehensive.

Chapter 3 (Paper I) presents quantitative results from a full-scale train-tunnel evacuation. The experiments conducted in the tunnel aim at investigating the differences in behavior and total evacuation times as a function of test sample. The experiments reveal results on reaction times and the social influence on these. Furthermore, walking speeds for sub-populations are found for each element of the egress path. All results on walking speeds are discussed and compared with the theory for able-bodied adults. Finally, the total evacuation time to empty the experimental setting is investigated.

Chapter 4 (Paper II) reveals the findings from the qualitative part of the train-tunnel experiment. Parallel to the full-scale evacuation experiments an interview study was conducted. The vulnerable test persons from the experiments were invited to take part in the interview study. The interviews were divided into three parts; one where basic characteristics were clarified, one concerning the participants experience with the experiments and lastly a survey on what buildings types they visit in their daily life and what challenges they meet.

Chapter 5 (Paper III) describes how the train-tunnel experiment is used as a basis to validate an evacuation model build up using the evacuation simulations software STEPS. The evacuation characteristics (walking speed and reaction times) found for the different sub-populations in chapter 3 are used as input parameters to the evacuation modeling software. The model is then validated against the train-tunnel experiment. The paper focuses on different modeling techniques and how they influence the predictions delivered by the software.

Chapter 6 (Paper IV) focuses specifically on evacuation characteristics of blind and visually impaired people. Different evacuation experiments are carried out and results on walking speeds horizontally and descending stairs as well as human behavior is presented. The degree of visual impairments is considered and is reflected in the results.

Chapter 7 summarises the findings obtained throughout the PhD study. The findings are compared and discussed across the core papers and give a general overview. The chapter is divided into sections summarising vulnerable peoples presences in buildings, their walking speeds horizontally and descending stairs. The human behavior observed in the experiments and verification of the evacuation modeling software is also summarized. The challenges identified by the vulnerable people, who took part in the experiments conclude the summary of findings. Lastly, a section describing the experimental limitations is included.

The core papers presented in chapter 3 to 6 are reproduced in the thesis as submitted or published. The layout is however changed to match the layout of the thesis. References are listed in a separate reference lists after each chapter presenting a core paper. References in core papers are not transferred to the main reference list. Duplicated or missing references might therefore occur.

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Chapter 2

Experimental Program

The results derived throughout the PhD study are based on a series of evacuation experiments held in various buildings and structures. Each experiment had a different focus and involved different segments of our population. The following section will describe the test sample in each of the experiments as well as the test locations. Methods for data collection and analysis of data is likewise given.

Experiments with heterogenous populations as well as visually impaired participants were conducted as a part of the current work. Data were collected for all experiments using temporarily installed video cameras to capture movement and behavior during the evacuation. The experiments had different setups depending on the test sample and the location. Some experiments were announced and the participants were given instructions in what egress route to use. Other experiments were unannounced and entailed full evacuation of the particular building or structure. Depending on the location different aspects of the evacuation process were in focus. The main focus areas were movement on the horizontal, movement on stairs, behavior during evacuation as well as the participants experience with the experiments and their use of different building types. The latter was investigated via interviews conducted in parallel to the experiments. It was not mandatory for participants to take part in the interview survey. Likewise they could opt out at any time during the evacuation experiments.

The experimental program consist of seven series of experiments held at six different locations. The number of participants in each series of experiments varied from 3 participants and up to 96 participants. One of the experiments involved a heterogenous population with seven subpopulations. The other six experiment only assessed evacuation characteristics of visually impaired participants. A complete overview of the experimental program is given in table 2.1. Each experiment is given a unique identification mark, that is used to distinguish the experiments from each other, when later referring to them. The three main focuses in the study is likewise given in the table and expressed by H,S and I for movement horizontally, movement on stairs and interview study, respectively. The experiments were conducted partly in Denmark and partly in the United States.

Table 2.1: Overview of experimental program. H = Horizontal movement, S = Movement on stairs, I = Interview survey. Locations A,D and F are office buildings, locations B and C are homes for visually impaired adolescents and location E is a railway tunnel, see section 2.2.

ID	Location	No. of participants	Test sample	Type of experiment	Trials	Focus
IBOS 1	A	3	Visual	Announced partly	8	HSI
IBOS 2	A	11	Visual	Announced partly	4	HI
SR 1	B	9	Visual	Unannounced full scale	1	HS
SR 2	C	7	Visual	Unannounced full scale	1	HS
DB	D	6	Visual	Announced partly	3	HSI
RESC	E	96	Mixed*	Instructed, full scale	20	HSI
WDC	F	11	Visual	Announced partly	5	HSI

* Able-bodied adults, elderly people, children, hearing, cognitive, visually and mobility impaired persons.

2.1 Test sample

The composition of the test sample varied in the seven experiments. In six of the seven experiments the test sample only contained people with visual impairments. In the seventh experiment, (Experiment E) the test sample comprised a heterogenous population. The heterogenous population consisted of able-bodied adults, elderly people, and children as well as people with different impairments, namely; hearing, cognitive, mobility and visual impairments.

The participants are characterised based on their subpopulation, gender, age, and aid, see table 2.2. It is known from previous studies that these characteristics influence an individual's evacuation capability [44, 47, 48, 72, 73]. The table likewise highlights in which experiment each subpopulation was present.

Table 2.2: Overview of test sample.

Population	Gender		Age	Aid	Exp. ID
	Male	Female			
Able-bodied	22	26	20-64	None	RESC
Elderly	4	7	≥ 65	None	RESC
Children	11	14	4-10	None	RESC
Hearing	3	-	20-33	Hearing Aid	RESC
Cognitive	3	1	9-26	Personal assistance	RESC
Mobility	3	-	23-69	Crutches, artificial limb	RESC
Visual[a]	9	8	10-19	Dog, white cane	SR 1+2
Visual[b]	19	14	20-64	Dog, white cane	All*
Visual[c]	1	3	≥ 65	Dog, white cane	IBOS 2, WDC

[a] Adolescents
[b] Adults
[c] Elderly
* IBOS 1+2, SR 1+2, DB, RESC, WDC

In total 148 persons took part in the experimental program, among them 75 males and 73 females. The age ranged from 4 years to 89 years and included seven subpopulations. The able-bodied adults aged between 18 and 64 years and did not have any permanent or temporary impairments, elderly participants were defined as persons aged 65 years or above without impairments according to themselves. The children were individuals aged younger than 12 years and likewise without any impairments. The participants with impairments should have a diagnosis corresponding to their specific impairment. Participants were recruited from different interest organizations, and the local community. Contact with participants was established via email correspondence, phone calls, emails, social medias, and information meetings held in possible participants immediate community. When participants had agreed to take part in the experiments, personal meetings were scheduled. This procedure was used for the announced and instructed experiments (IBOS1+2, DB, RESC, and WDC). The personal meetings resulted in a showing up rate above 95%. The participants use of aids were dependent on whether they had an impairment or not. The able-bodied, elderly people and children did not use any aid during the experiments. The hearing impaired participants used hearing aids and sign language. The mobility impaired individuals used crutches and artificial limbs, dependent on the nature of their impairments. Three of the four cognitive impaired participants were accompanied by an assistant. The visually impaired participants used a white cane and some where also accompanied by a guide dog.

The background and composition of the heterogenous population were based on the demographic profile of Denmark [74–77]. It is assumed that the demographic profile of Denmark is representative for the population in many western countries. Though, the experiments were conducted in Denmark and United States. Testing a heterogenous population is assumed to reveal results that are affected by human behavior. Where on the other hand homogeneous groups are assumed to give results, which are biased by a uniform group of people with similar characteristics. Hence, such results can be used as input parameters. However, studies have shown that social influence and human behavior affects an evacuation flow, [70,73,78–82]. Results derived from experiments with heterogenous test groups are therefor needed to clarify how large the effect of human behavior are on evacuation characteristics.

The segment of visually impaired participants was further divided into adolescents, adults and elderly, since their age is expected to affect their evacuation characteristics and capabilities. Besides the division into age groups, the degree of vision loss was registered. The degree of visual impairment is determined based on the international classification given by The World Health Organization (WHO), [83]. The WHO classification consist of five categories (1-5), where people with least reduction of their sight is placed in category 1. The degree of vision loss is determined by the person's visual acuity and is measured as the relation between what a normal sighted person can see at a certain distance and at what distance the visually impaired person can see the same object (example: a normal sighted person can see an object at 60 meters. The person with visual impairment can see the same object on 1 meter, hence the visual acuity is 1/60 corresponding to category 4). It is the persons best eye that determines the category and the visual acuity. The participants in the experiments were also characterised based on their vision loss. Table 2.3 shows the composition of the group of visually impaired participants.

Table 2.3: Composition of visually impaired test sample.

Age Group	Category					Aid*		
	1	2	3	4	5	Dog	Cane	None
Adolescents	7	-	6	6	-	-	-	19**
Adults	-	9	4	14	4	9	14	15
Elderly	-	1	1	1	1	1	3	-
Total	7	10	11	21	5	10	17	34

* Some participants used both cane and were accompanied by a guide dog.
** Some adolescents were assisted by normal sighted adult staff.

As shown in table 2.3 54 visually impaired participants were involved in the experiments. Almost half of the visually impaired participants had a visual acuity equal to or less than $\frac{1}{60}$ and some of them were completely blind without any light perception (participants in category 4 and 5). In order to navigate in a building the participants use different kind of aids. The group of adolescents did not use the traditional aids such as white cane or guide dog. They were guided by normal sighted staff or special marks along the egress path. Furthermore, this group lived in the building where the experiment were conducted and were very familiar with the environment. Ten of the remaining participants (adults and elderly) were accompanied by a guide dog during the experiments, and 17 used a white cane. Additionally, 15 of the adult participants did not use either guide dog or cane. However, some of them were guided by normal sighted persons. The use of aid is assumed to influence an individuals confidence while navigating in a building. Since a blind or visually impaired person cannot rely on their sight, they need to trust what they sense with either the cane or trust their dog on which way it is leading them.

Worldwide, it is estimated that 285 million people have a visual impairment. Out of these 39 million are blind and 246 million have low vision [84]. The segment of the population with visual impairment thus constitute nearly 4% of the total population. The prevalence of people with visual impairment increases with age and 82% of those living with low vision is above 50 years. In the experiments 19 of the 54 visually impaired participants is above 50 years. Consequently, the group below 50 years is over-represented in the experiments comparing with the worldwide trend. Statistics show that 69% of the population aged 45 to 54 years in United States need corrective eyewear and for the population aged 55 and older the percentage is 79%, [85]. Hence, a very larger proportion of the population might be challenged visually.

2.2 Test locations

The experiments were conducted at six different locations. Five of the locations were regular buildings, whereas the sixth location was a tunnel. The participants familiarity with the structure varied between the different locations, and the same participant did not perform experiments at more than one location, except for one person.

Location A is an office building, 2 storeys high, and was built in 1966 as an institution for blind and visually impaired children. It is located north of Copenhagen, Denmark. Today the building is used by The Institute for the Blind and Partially Sighted (IBOS). IBOS function as the national competence- and rehabilitation centre for young and adults with visual impairments. The main routes for evacuation are via corridors and staircases. The main staircase and entrance is located in the middle of the building and two emergency staircases are provided in each wing of the building. To initiate the exercise a local warning system consisting of a bell was used.

Location B is a housing facility for blind and visually impaired adolescents. The building, from which the experiment was conducted, is a part of a housing complex and school for children with visual impairments. The building functions as the adolescents home away from home, and they each have their own room. The building had two storeys and a basement. The basement was not considered in the experiment. The egress path was mainly though corridors and stairs. There was one stair in the middle of the building considered as the main stair and two additional stairs in each end. The existing warning system (tone alarm) in the building was used to initiate the experiment. The participants were situated at the ground floor and the first floor when the experiment began.

Location C is a part of the above mentioned school and housing facility for blind and visual impaired adolescents. This location is another house, where the adolescents live while away from home. The division into several houses is based on how self-supporting the inmates are and their age. This building is also a two storey building with an additional basement. There are two staircases in each end of the building and the main entrance is placed in the middle of the building. The participants were located on the ground floor and the first floor when the experiment was initiated. The built-in warning system in the building was used to start the exercise (tone alarm).

Location D is an office building hosting the Danish Association of the Blind. The section of the building where the experiment was conducted had three storeys and the experiments were initiated from the second floor and were terminated when the participants reached the ground floor. The egress path consisted of corridors and stairs. Local warning was used to initiate the experiment.

Location E is a full scale test tunnel similar to the railway tunnel connecting Zealand and Funen in Denmark. The tunnel section is 60 meter long with two transversal tunnels. The internal distance between the transversal tunnels is 40 meters. An IC-3 train, similar to the trains used in daily operation of the railway link, is situated inside the test facility. The test facility is provided with an emergency pavement with a width of 1.3 meters. The train has a capacity of 23 seated passengers. The central communication system in the train was used to initiate the experiment.

Location F is an office building in Washington DC, USA. The building is a 6 storey building hosting an administration company. Horizontal movement is distributed via long corridors up to 100 meters. There are emergency staircases in each end of the building and one in the middle. During normal use of the building vertical movement is distributed by elevators. The experiment was initiated using local warning. The warning was only given in the room, where the participants were situated prior the experiments. All participants were seated in the same meeting room on the fourth floor and the experiments were initiated from this room. The experiments were terminated when the participants reached the second floor.

Schematic drawings of the egress routes for each of the six locations are provided in appendix I.

2.3 Setup of Experiments

The setup of the seven experiments was governed by the layout of the building form in which each experiment was conducted. In some of the buildings only partial evacuation was carried out and in others a full evacuation was completed. Data were collected based on three different stages of evacuation; single evacuation, group evacuation, and full scale evacuation. The single and group evacuation was controlled by the research team and the purpose of these experiments was to measure free walking speed and capture interactive behavior between people in a group. In addition, unimpeded movement paths were determined. The single and group evacuation partially lack realism, since the participants were instructed beforehand and they knew exactly what emergency route to use. In some of the experiments the participants did not have to leave the building in order to reach a place of safety. Four of the seven experiments were carried out as single and group evacuation experiments (IBOS 1+2 (loc. A), DB (loc. D) and WDC (loc. F)). In the two unannounced full scale experiments (SR 1+2 (loc. B and C)) the participants were instructed in the buildings' evacuation procedures in the week before the experiment, but the exact time was not announced neither was there a pre-determined emergency route. The purpose of the full scale experiments was to determine total evacuation time, free unimpeded walking speeds as well as walking speeds influenced by higher person densities. Furthermore, the interaction between participants was registered. The last experiment (RESC, loc. E) was a full scale experiment, but it was held in an unfamiliar environment and the participants received basic instructions prior the experiments.

The unannounced full scale experiments conducted at location B and C were only ran once (SR 1+2). The full scale experiments performed in the tunnel (RESC, location E) was conducted with four setups, each with a different composition of the test sample. Each of the four setups were replicated five times resulting in a total of 20 trials. For the partial and instructed experiments the number of trials varied and so did the size of the groups. The first experiment conducted at location A, (IBOS 1) was only carried out as single evacuation. The participants moved along different emergency routes and in total eight trials were completed. The second experiment conducted at location A was only evacuation of groups, and all groups were situated at ground floor (location A, east wing). The two groups consisted of five and six individuals, respectively. The two groups evacuated twice via two different emergency routes. Hence, four trials were completed. Experiment DB, carried out at location D, consisted of three trials, where the participants evacuated alone (single evacuation) and in groups of three and six persons. In the last experiment (WDC, location F) the participants accomplished single evacuation and evacuation in groups of two, three, five, and eleven persons. An overview of the experiments are given in table 2.4.

Table 2.4: Overview of setup of experiment. S = Single evacuation, G = Group evacuation, F = Full scale.

ID	Loc.	No. of participants	Type	Instructed	Familiar	Repeated
IBOS 1	A	3	S	Y	Y	Y
IBOS 2	A	11	G	Y	Y	Y
SR 1	B	9	F	N	Y	N
SR 2	C	7	F	N	Y	N
DB	D	6	S,G	Y	Y	Y
RESC	E	96	F	Y	N	Y
WDC	F	11	S,G	Y	N	Y

2.3.1 Movement - Horizontal planes

All movement was captured using temporarily installed video cameras. Cameras were mounted using different equipment, e.g. suction cups and clamps, allowing a flexible setup of cameras modified to the current location. Different mounting options can be seen in figure 2.1.

Movement on horizontal planes was primarily through corridors. The camera settings and position varied between the experiments due to the layout of the test locations. The cameras were positioned in two different ways - turning an angle and filming directly from above, see figure 2.2. The cameras that were turned an angle were used to identify human behavior and interaction between participants and their interaction with the environment. The cameras filming directly from above were used to determine person densities and passage of checkpoints.

Figure 2.1: Mounting options for cameras using suction cups, clamps and moveable bars with pipe clamps.

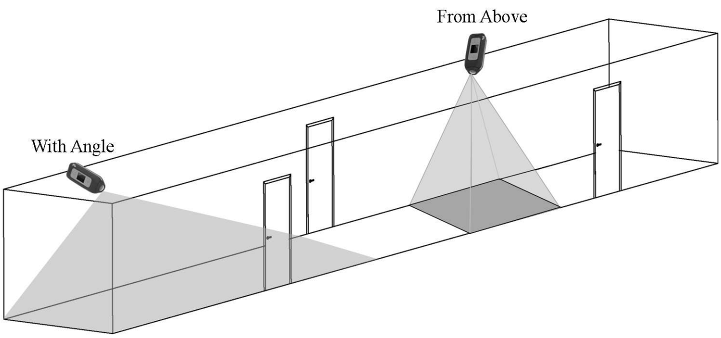

Figure 2.2: Mounting of cameras filming from above and with an angle, [86].

The internal distance between the cameras in the corridors varied between 1 meter and up to 15 meters. The number of cameras used to cover the corridors in the different test locations also varied from 11 cameras and up to 39 cameras.

2.3.2 Movement - Stairs

Participants movement on stairs was likewise recorded using the temporarily installed video cameras. Each stair flight was covered with two cameras; one filming down the flight and one filming up the flight, see figure 2.3. The two cameras filming in opposite direction ensured that people hidden behind another person were visible on the other camera. Furthermore, the start and end of the flight was easier to identify. Each landing was filmed directly from above to determine person densities and movement paths.

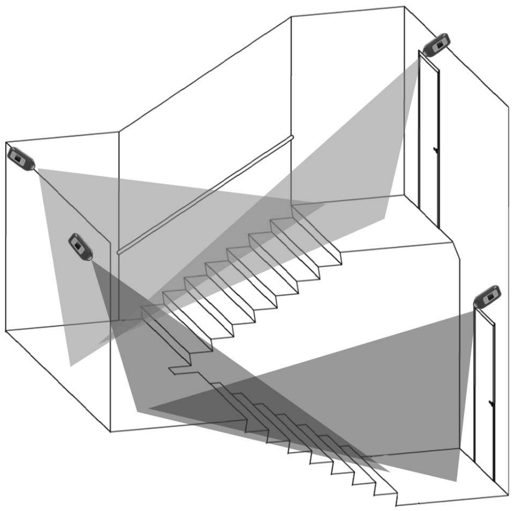

Figure 2.3: Camera setting in staircases.

2.3.3 Interview session

Parallel to the evacuation experiments, an interview study was conducted. The interview study was related to the evacuation experiments and was carried out directly after the physical experiments. The purpose of the interview was to clarify the vulnerable participants' experiences with the experiments as well as their use of different kind of buildings. The interview was based on a questionnaire that consist of three parts, reproduced in appendix N. In the first part the participant was identified and certain characteristics were specified. Among the characteristics of interest were gender, age, type and degree of impairment, origin of impairment, and use of aid. In the second part of the interview the participants evaluated their experience with the evacuation experiment. This second part both contained factual and emotional questions assessing different aspects of the evacuation experiment. The factual questions were e.g. used to clarify the respondents' positions in the building or train. The purpose of the emotional questions was to assess the respondents' psychological perceptions of the experiment. The focus of the third and last part of the interview was on the respondents use of different building types, and accessibility and egressibility of these buildings.

The questionnaire was adjusted to fit the specific experiments and subpopulations. However, the overall scope was the same for all interviews. The questionnaire used in interviews conducted in relation to WDC is available in appendix N. It was not mandatory for the participants in the evacuation experiments also to take part in the interview study. Furthermore, interviews were not conducted in relation to the unannounced full scale experiments (SR 1+2). In total 28 participants took part in the interview survey.

2.4 Data Analysis

All experiments were recorded using temporarily installed video cameras. The cameras were light weighted action cameras recording with a wide angle of 170 degrees and with a rotatable lens. The native format of recordings was 30 frames per second. The wide angle entailed a need for reference points to determine distances on the recordings. To ensure sufficient reference points a chequered mat was used as an underlaying picture though the analysis. The analysis was conducted manually using a video processing software. It would have been preferred to automate the data processing process, but no software are currently available. There exists different tracking software solutions, but none of them are able to track a person between different cameras and often the participants need to wear some specific marking. Furthermore, the specific position of the camera is important for the tracking software. Since the experiments were held in natural environments, it was not possible to fulfil these requirements.

Recordings were loaded into the software. Here it was possible to place the chequered mat under the recording and make the film transparent, see example in figure 2.4. Thereby, it was possible to determine the time when each participant passed a pre-defined checkpoint. There was made a synchronization between the cameras to give the same relative time and thereby follow each participant from camera to camera.

Results are compared with the theoretical model developed by Nelson and MacLennan, [67]. This model is developed based on extensive data given by Fruin, Pauls, and Predtechenski and Milinski, [7–9], and is one of the most widely used models to describe walking speeds in relation to increasing person density. The studies conducted by Fruin, Pauls, and Predtechenski and Milinski were conducted in 1971, 1980 and 1978 respectively. Hence, the data were collected many years ago. In addition, the data were collected to assess pedestrian movement in buildings and structures under normal conditions and not during emergency situations.

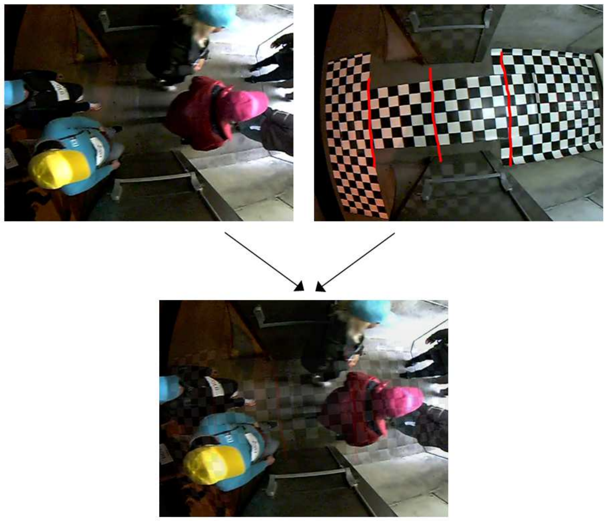

Figure 2.4: Method to merge recordings with chequered mat.

2.4.1 Walking Speed

The walking speed is measured in meters per second both horizontally and descending stairs. Horizontally, the walking speed is measured as the time it takes to pass between two natural checkpoints along the egress route. The walking speed obtained using this method is then the average walking speed between the two points. The distance, over which the walking speed is measured, varies from experiment to experiment due to different distances between the natural checkpoints and position of the cameras. The distance between checkpoint is in a range from 1 meter up to 7.5 meters.

The walking speed descending stairs is measured as the diagonal travel distance divided by the time it takes the person to descend that specific flight of stairs. Hence, the walking speed on intermediate landings is not included. A person has started the descent in the moment he/she lift one foot and bends the opposite knee to take the first step. Contrary, the person has left the stair as soon as he/she shifts the full body weight to the foot on the landing and the other foot is lifted from the last step. The travel distance for a flight of stairs is defined according to equation 2.1, where l_{going} is the depth of the going, l_{rise} is the height of the rise and N_{steps} is the number of steps.

$$l_{stair} = \sqrt{l_{going}^2 + l_{rise}^2} \times N_{steps} \tag{2.1}$$

The dimensions of the stairs varied between all seven experiment and the dimensions of going, rise, nosing depth, and number of treads are outlined in table 2.5. According to the theoretical model developed by Nelson and MacLennan, [67], the dimension of the stair influences the walking speed and is dependent on depth of the tread and the height of the rise. All stairs in the experiments have a nosing depth. Hence, the full depth of the tread is not used to calculate the length because the gradient would be lower than what the participants experience during their descent of the stair.

Table 2.5: Stair geometry in experiments.

Exp. ID	Stair no.	Rise (cm)	Going (cm)	Nosing depth (cm)	Width (cm)	No. Treads
IBOS 1	1	16	31.5	2.5	200	9
IBOS 1	2	16	28	4.5	121	9
IBOS 1	3	17	28	4.5	121	9
SR 1	1	18	22.5	4.5	87	3
SR 1	2	18	25.5	4.5	87	8
SR 2	1	17.5	25	5	87.5	7
SR 2	1	17.5	25	5	87.5	13
DB	1	17.5	25.5	4.5	102	8
DB	2	19	23.5	4.5	100	8
RESC	1	23	23.5	3.5	125	3
WDC	1	20	30	4	125	10

2.4.2 Person Density

The person density is an important measure and related to the walking speed. The walking speed can be expressed as a function of the person density. There exists different definitions and methods to calculate the person density.

The classical definition of the person density used in experimental studies on pedestrian dynamics is the number of pedestrians divided by a given area [87,88]. This definition will then have the unit $pers/m^2$ and gives an average density over the given area. This definition is very dependent on the size and geometry of the area, where the density is measured. Local and global densities might consequently vary substantially. The reference area should therefore be chosen with caution.

Another method to calculate the person density is to apply Voronoi diagrams [89]. The Voronoi method entail that persons are seen as particles without no physical extent. An area is assigned to each person and the size of the corresponding Voronoi cell is controlled by the distance to other particles in the vicinity. Boundaries are defined so that every point in the area is closer to the particle than to any other one. The drawbacks using the Voronoi method is that persons at the edge of a group will have cells that extend to infinity. In addition, the body shape and sway is neither accounted for.

A third method is proposed by Predtechenskii and Milinskii [8]. In their approach they consider the physical representation of the human body. They define the density as the ratio of the sum of horizontal projections of people to the floor area occupied by the studied flow. Hence, it is possible to distinguish between the size of people. This method will give a dimensionless result, m^2/m^2, but the developers have defined a function to switch between m^2/m^2 and $pers/m^2$.

In the current study, it was decided to calculate person densities using the classical method, but using the same size of reference area for all measurements.

The theoretical relation between walking speed and person density can be expressed by equation 2.2, where v is the walking speed in m/s, k is a constant dependent on egress route element e.g. stair, corridor, etc., and D is the person density measured in $pers/m^2$. This relation between walking speed and person density is developed by Nelson and MacLennan, [67].

$$v = k - 0.266kD \tag{2.2}$$

In the data analysis of the experiments the person density on horizontal planes is determined based on a reference area of 2 m^2. The physical representation of the reference is strived towards one meter in front and behind the person and one meter of width, see figure 2.5. However, the layout of the egress routes entailed that, this was not possible for all experiments. Furthermore, the internal distance between the checkpoints between which the walking speed was measured influenced the way the density was measured.

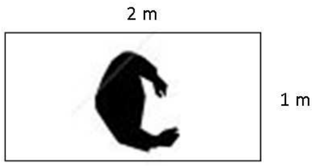

Figure 2.5: Reference area around studied person.

Measurement of person density on stairs was done differently than for horizontal planes. For stairs the density was measured as the average number of persons present on the stair in the same time interval as the person in question was present on the same stair flight. Practically, the number of persons entering and leaving the stair, during the same interval as the person in questions was present on the stair flight, was registered. The number of persons entering the stair were then subtracted the number of persons leaving the stair. The average number of persons was then divided by the area of the stair. The area of the stair was calculated as the area of each tread multiplied by the number of treads. The area under the nosing depth is not accounted for in the calculation of the tread area for people descending stairs.

Throughout the PhD project all results are compared with the combined evacuation model for able-bodied people, referred to as the Nelson and MacLennan theory abbreviated N&M.

2.5 Ethical Considerations

Performing experiments with human beings in Denmark require approval from two authorities; The Danish Data Protection Agency and The National Committee on Health Research Ethics. The project was registered and approved by the data protection agency under journal number 2011-41-6440. Certain conditions regarding data storage and processing of data were outlined and followed. The project was likewise filed to the ethical committee. The legislation in Denmark, however, entail that research classified as registration research is exempt from the obligation to notify. But only if the research does not include any biological material. Even though approval by the ethical committee was not required the requirements and recommendations, outlined by the committee, were followed. Accordingly, all participants signed an informed consent prior the experiments, and if possible they received both oral and written information about the project and experiments. Furthermore, the participants could withdraw at any time during the experiments and were not exposed to any fire hazards or other extra ordinary conditions during the experiments. The research team developed an internal codex which is available in appendix J. Participation was on an entirely voluntary basis and the participants were not rewarded, but received a small appreciation gift.

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Chapter 3

Evacuation safety for everyone? A quantitative study on a train-tunnel experiment accounting for vulnerable people

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Thesis Paper	I
Title:	**Evacuation safety for everyone?** A quantitative study on a train-tunnel experiment accounting for vulnerable people
Author:	J.G. Sørensen and A.S. Dederichs
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Abstract

The current paper presents a study on a full-scale evacuation experiment in a tunnel in Denmark. The effect of heterogeneity is studied. Furthermore, evacuation of people without regarding for age and impairment is investigated. The group of participants comprised people in the age range of 5-84 as well as people with cognitive, mobility, visual, and hearing

The total evacuation time is doubled for a mixed group compared to a homogeneous group. The N&M curve is conservative compared to the data of the able-bodied and the hearing impaired, but not for the other populations. The walking speed of all populations is affected by increasing densities. However, the walking speed of people with visual impairments is least affected by increasing density, as observed for people with reduced sight due to smoke. The degree, to which the walking speed is affected by the density, seems to be affected by how many people can be identified in a person's viewing angle. The highest density of 2.31 $pers/m^2$ was attained by the children

As a general observation, it is found that the reaction times for the persons within the same seating group are comparable. The normative social influence is strongest among people that belong to a group formation compared to people acting individually.

The study shows the importance of considering the composition of the population in relation to fire safety design. Here it is necessary to include information on the evacuation characteristics of all subpopulations.

Introduction

Tunnel safety is an important topic, not only with respect to road tunnels, as it became clear with the incidents in Mont-Blanc tunnel in 1999 and Gotthard tunnel, 2001; but also with respect to train tunnels, as shown with the Severn Tunnel rail accident in 1991 and the Kaprun disaster, causing 155 fatalities [PI-1]. Train tunnel systems in larger cities might be complex, and likely to involve a large number of passengers. An ineffective evacuation of such complex train-tunnel systems may have severe consequences for evacuees, especially for passengers with disabilities, as shown in the example of London Underground Limited [PI-2].

Studies conducted in the United States, Denmark and Japan have shown that the fire fatality rate for members of the vulnerable part of the population is higher compared to with able-bodied individuals [PI-3 - PI-5]. The vulnerable segment comprises individuals with physical and cognitive disabilities, individuals aged younger than 5 years or older than 64 years as well as people impaired by drugs or alcohol. However, the studies conducted in the United States revealed that the company of able-bodied adults reduced the risk of death for this group of individuals [PI-3]. Facing a higher fatality rate for the vulnerable segment of the population raises the question "Is fire safety in buildings and structures sufficient for the vulnerable segment of the population?".

Codes and Legislation
Traditionally, fire safety has been addressed through the application of prescriptive fire safety codes, the so-called prescriptive codes. In many countries, the prescriptive codes have been replaced by performance based codes. This process of replacement of legal principles started in Europe in 1975 with Iceland introducing performance based codes, followed in 1985 by England, 1994 by Sweden and Belgium, 1997 by Norway and Finland, 2005 by Scotland, 2006 by Spain and 2007 by Italy [PI-6]. The prescriptive codes were evolved in similar ways internationally. As an example Denmark will be used for providing the background in this section. In Denmark the performance based fire safety codes were introduced in 2004. The application of these codes in Denmark has implied a categorization of buildings according to type of occupancy [PI-7]. The Danish categorization is based on occupant load within each fire compartment, daytime/nighttime use, knowledge about the building and egress system, and the ability to evacuate unassisted. Six categories are established by combining the listed parameters. Five of the six categories (1-5) refer to people that are able to evacuate unassisted. Hence, only one category (6) is available for people with disabilities, children and elderly, who are assumed to have a need for assistance during an emergency evacuation.

However, many buildings in category 1-5 will be frequented by occupants with both temporary and permanent impairments. The authors therefore emphasize that the vulnerable part of the population should also be accounted for in buildings placed in category 1-5. Around the world, different legislation and guidelines have been developed to ensure the egressibility of people with different impairments. The British Standard Code of practice (BS9999) provides an extensive description and recommendations regarding fire safety measures to take in relation to disabled people [PI-8]. It prescribes that the full range of people should be considered and special attention to the needs of disabled people should be given. Furthermore, the code provides requirements and recommendations for different groups of disabilities e.g. mobility-impaired, wheelchair users, deaf or hard hearing people, blind or partially sighted people, and people with cognitive disabilities. It is recommended that personal emergency evacuation plans are prepared for all people that will require assistance to leave a building. Furthermore, safe refuges should be established in the building, and the code provides examples on how to design these areas. In the United States of America, it is required by law though the Americans with Disabilities Act (ADA) that needs of people with disabilities are addressed in an emergency evacuation plan. This requirement is however only valid for public accommodation [PI-9]. Essentially the ADA states that whatever is done by building owners or first responders for anyone must be done for everyone. Hence, the ADA outlines requirements on accessibility for new constructions and alterations in existing buildings as well as specific requirements for public accommodation and commercial facilities [PI-10]. As a supplement, the National Fire Protection Association has published the "Emergency Evacuation Planning Guide for People with Disabilities" [PI-11]. The intention with the guide is to give advises on issues relevant for a person's ability to evacuate a building in the event of an emergency. The guide is divided into chapters concerning the five types of impairments namely mobility impairments, visual impairments, hearing impairments, speech impairments, and cognitive impairments.

In New Zealand building owners are required to designate one or more places in the building where people with disabilities can gather in case of fire if they are unable to evacuate using the building's means of egress. In addition, it should be specified in a so called evacuation scheme how firefighters are notified about the designated places and if people are present in the given areas during an incident [PI-12]. Contrary, a study from Ulster University shows, that people feel uncomfortable not being able to participate in an evacuation and waiting for rescue in a safe place or refuges [13]. The study showed that 60% of respondents reported that they presumed to feel uncomfortable remaining in a safe place for a period longer than 10 min without assistance. Concerns mentioned in the study were 'being forgotten', 'lack of information/communication on the waiting time prior to assistance arriving', and 'being left alone' [13]. Furthermore, todays fire safety design, does not enable a prediction on when the rescue will be performed. It is therefore important to consider people with temporary or permanent disabilities in a fire safety design in order to ensure equal egress. This will be a further step towards providing the same safety level for people irrespective of impairment [PI-14].

The development and implementation of performance based fire safety codes allows a more free design. Furthermore, the past decades have shown an increasing interest and recognition of complex buildings and structures. The performance based codes then allow the fire safety engineers to apply fire safety engineering tools such as computer models to investigate and ensure a sufficient safety level in the current building or structure instead of fulfilling prescribed requirements. Software describing the development of a fire in a building, e.g. CFD codes are used to compute the time until untenable conditions occur. This time is the available safe egress time. On the other hand, evacuation models are used to estimate the required safe egress time. The overall requirement is that no one may be exposed to critical conditions during the evacuation. Hence, the available safe egress time need to be larger than the required safe egress time with a certain safety margin. The latter software is based on numerous studies on evacuation and movement of people with normal mobility who are able to evacuate themselves, [PI-15 - PI-18]. There exists varies evacuation models that are developed for different purposes and validated differently [PI-19].

Literature Review
A study performed by Kuligowski et al. investigating available evacuation modelling software revealed that 42% of the examined models use movement data from three sources namely Fruin, Pauls and Predtechenskii and Milinskii [PI-19]. The data used as reference for the movement was collected more than 30 years ago and the demographic profile have changed since then. Even though the data was collected long ago, it is still the most comprehensive data available and is widely used around the globe. None of the data was derived from real emergencies and the characteristics of the test subjects were able-bodied adults, mainly males. The studies conducted by Pauls originated from evacuation drills in tall office buildings in Canada whereas the results derived by Fruin came from transport terminals, [PI-15, PI-16]. The latter study by Predtechenskii and Milinskii was performed in the Soviet Union during normal use of public buildings [PI-17]. However, homogeneous groups of able-bodied adults are rarely representative for the population in a building. Due to changes in society a more representative population in a building would include children, elderly people and people with disabilities. Depending on definition, statistics show that 10-20% of the population worldwide has some kind of disability [PI-20 - PI-22]. Other studies have revealed that the prevalence of people with disabilities increases with age and with an ageing population a large proportion of the future building occupants will presumably have some kind of disability [PI-23 - PI-25]. Therefore the segment of disabled people in our society needs to be safe in case of emergency in the same way as able-bodied adults.

In the literature limited data on evacuation capabilities of disabled people can be found. Movement speeds on stairs has been investigated via studies performed by Kuligowski et al, Proulx et al., Boyce, Shields and Silcock as well as Fujiyama and Tyler, [PI-26 - PI-29].

Fridolf et al. (2013a) performed a trial in Europe, simulating an evacuation of able-bodied adults from a smoke-filled car-tunnel [30]. Former results were confirmed showing that walking speed was reduced with decreased visibility, providing a decreased walking speed for a range of visibilities. Unimpeded walking speeds in smoke of 0.9 m/s were found by Fridolf et al. [PI-31]. Likewise, Sorensen and Dederichs showed that walking speed decreased with decreased visibility for visual impaired persons [PI-32].

The effect of training in a virtual reality experiment was conducted by Kinateder et al., [PI-1]. The experiment was in a simulated car tunnel with driving evacuees. The effect of training and information prior the simulated incident on the process of effective decision making and route choice was shown. Modeling of evacuation of two passenger trains using STEPS was conducted in another study. Both trains had a length of 200 m and with two locomotives. One had 12 railway wagons and 318 passengers and the other 8 railway wagons and 400 passengers. The four scenarios were with two fires inside and two outside the train [PI-33]. Regarding the fire inside the train it was shown that ladders to help exiting in case of blocked doors are essential. It is also important to apply an appropriate management of person flows to minimize congestions and overcrowding during an evacuation.

Real evacuation incidents in China where a train in a tunnel was emptied showed velocities of 1.5 m/s at free speed densities and velocities less than $0.1 m/s$ for a maximum density of 2.8 $pers/m^2$ [PI-34]. Different designs and scenarios involving platform screen door systems were investigated by Qu and Chow, providing data on total emptying times for different door reductions in crowded situations [PI-35].

Procedures and total evacuation times were investigated by Capote et al. using STEPS and as input a real evacuation drill involving able-bodied participants in Europe. It was shown, that a relocation of passengers inside the train is essential for optimizing the evacuation strategy in case of fire on board of the train. The total evacuation time to the platform was found to exceed 90 seconds [PI-36].

A series of evacuation experiments focusing on the design of trains in the context of evacuations for elderly people and people with disabilities have been carried out [PI-37 - PI-39]. Design criteria such as the horizontal gap between train and platform has been shown to be optimal being 2x2cm [37]. The evacuability of a train was determined by the vertical gap height. The evacuability is limited for elderly people at heights above 35 cm [PI-38] and above 64 cm for able-bodied people evacuating in smoke [PI-39]. Furthermore, it could be shown that evacuation time increases with the height between car and platform [PI-40].

The goal of the paper is to study the effect of heterogeneity of the population on evacuation times in a real train-tunnel experiment. For this a group of able bodied and groups of people containing able bodied people as well as elderly people and children and people with different disabilities was carried out. The goal is to deliver quantitative data applicable in models, software and guidelines on reaction times, walking speeds and free speeds for the different groups. The paper is built up in the following way: method for data collection are presented in the next section, followed by a presentation and discussion of the results dealing with the reaction times, walking speeds on the horizontal and down the stairs as well as the free speed. The qualitative results of the study can be found in "Evacuation safety - for everyone, A study on access and egress of people with impairments" by Sorensen and Dederichs [PI-41].

Methodology and data collection

Experimental configuration and location/setup
The evacuation experiments were held in a full-scale model of the Great Belt Link, connecting Zealand and Funen in Denmark. The full-scale test tunnel is located at REscue and SecurityCenter (RESC) in KorsÃ¸r, and the experiments were conducted in May 2012. The full-scale test tunnel is a 60 meter long tunnel section similar to the real tunnel. The model is constructed with two transversal tunnels with an internal distance of 40 meters. The transversal tunnels are separated from the main tunnel with double doors made of steel and equipped with a panic bar. Similar doors are used as exit doors from the transversal tunnel to the outside. The tunnel is likewise equipped with exit signs, emergency telephones, and emergency lightning corresponding to the real tunnel. The evacuation experiment is initiated from an IC3 train situated at one end of the test tunnel. The train in the test tunnel consists of one coach, decorated as a normal operating train. The train coach is designed with 20 seats distributed with four seats in five seating groups (SG2-SG6) and three additional folding seats next to the exit (SG1), see figure 1. Besides the seated passengers the experiments are designed with 13 standing passengers in the train coach and an additional 10 passengers in the train lobby. The train lobby is only for standing passengers. This gives a maximum passenger load of 46 persons. It might seem as a high passenger load in a relatively restricted area but it is not unusual in Denmark to have overcrowded trains during peak hours [PI-42].

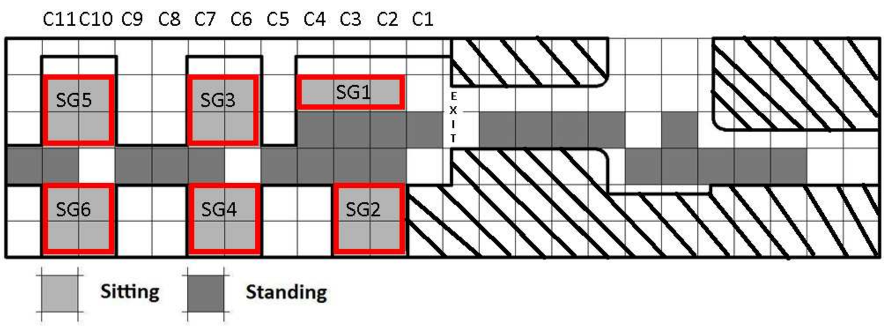


Figure 3.1: Position of participants in train carriage. Indication of seated and standing passengers and seating groups (SG). The grid is named based on columns C1-C11.

There is a three-step stair from the train lobby to the emergency pavement in the main tunnel. The train is equipped with a central communication system, which is used to verbally announce the evacuation. Only verbal warning was used during the experiments. The participants received the following message:

"Message to all passengers. Smoke is observed outside the train and the train needs to evacuate. All passengers are asked to leave luggage and belongings behind and leave the train. When you exit the train turn left to the nearest transversal tunnel". The passengers do not receive any further instructions on how to exit the train and tunnel except that it should be completed in a safe manner. In addition they are informed that this is not a competition but a question of getting everyone out in a safe way. The evacuation route from the train coach is through the train lobby, down the three steps with a width of 1.25 meters to the emergency pavement with a width of 1.3 meters. After exiting the train the passengers walk 4.4 meters in the main tunnel before taking a 90° right turn into the transversal tunnel. The length of the transversal tunnel is 6.8 meters and the passengers are considered safe when they exit the transversal tunnel and reach outside see figure 3.2.

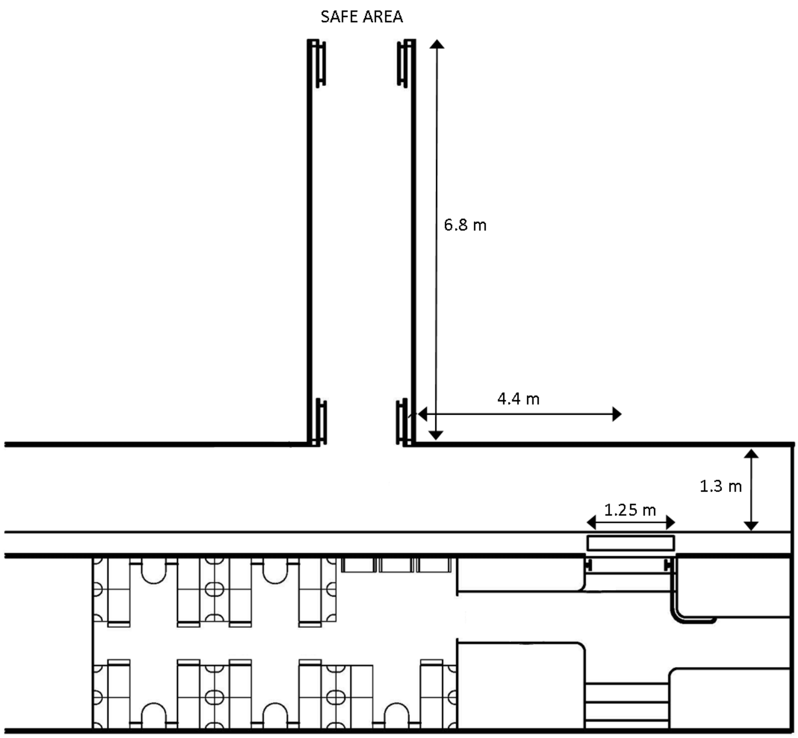


Figure 3.2: Layout of train and tunnel.

Experimental setup

Four experiments were performed each with a different composition of the test population. In the following paragraph the four experiments are referred to as setups. The four setups differ on the composition of the population. The compositions are based on statistics regarding the demographic profile of Denmark. The goal is to study the effect of the heterogeneity of the population on the evacuation, and also account for the effect of the presence of different vulnerable groups on the evacuation process. There are three setups with a varying composition of the population and one setup with only able-bodied adults. The first setup comprises able-bodied adults, elderly people and children as well as people with cognitive, hearing and visual impairments. The composition of the second setup is similar to the first setup, but the people with visual impairments are replaced with people with mobility impairments. In the third setup the basis is able-bodied adults, elderly people, and people with cognitive and hearing impairments. In addition people with mobility and visual impairments are presences, whereas no children are participating. The fourth and last setup is the reference setup only comprising able-bodied adults. The maximum capacity of the train allows for 46 passengers. Table 3.1 gives an overview of the four setups and shows the size of each subpopulation for each setup.

Table 3.1: Composition of test population in each of the four setups

	Setup 1 - mobility impaired	Setup 2 - visually impaired	Setup 3 - children	Setup 4 Only able-bodied
Able-bodied	23	22	27	39
Elderly	7	7	8	-
Children	8	10	-	-
Hearing impaired	3	2	3	-
Cognitive impaired	2	2	2	-
Mobility impaired	-	3	3	-
Visually impaired	2	-	2	-

Each setup is replicated five times giving a total of 20 runs divided between four setups and five runs. Seating of the participants are determined prior the experiments and is chosen randomly. Before each run the participants are therefore assigned different position in train carriage and lobby.

Participants
The participants are mainly recruited from the local area around KorsÃ¸r. Initial contact was established via posters, emails, and information meetings. The showing-up-rate was 97% of the people that showed interest in the experiment. The total number of participants was 96 persons and comprised of 48 able-bodied adults, 25 children, 11 elderly people, 4 cognitive impaired, 3 persons with mobility impairments and hearing impairments respectively and 2 persons with reduced vision. The able-bodied adults were in the age from 17 years up to 64 years and with a large variation in their physical shape. The children were recruited from a local school class and their age was in the range from 5

to 8 years whereas. The elderly people were from 65 years up to 84 years and did not have any self-reported impairments. The participants did not have any prior relationship to each other and none of them knew each other before hand, except for the children. The participants spent a full day at the experimental location and were served breakfast and lunch and it was observed that some participants developed relationships during the day. On the arrival each participant was given a bag with an individual program of the day with specific schedule for their participation in the experiments. In addition each participant got an identification number and a cap with a color corresponding to their subpopulation. Caps and numbers are used to identify the participants on the video recordings.

Data Collection

Data was derived from video footage and manual observations. The video footage was collected using temporarily installed video cameras. The cameras were action cameras with a rotatable lens and they were filming with a wide angle of 170 degrees. The video films were recorded with 30 frames per second, and the raw video footage was analysed frame by frame after the experiment. The train carriage and the egress path are covered with 24 cameras. Two different filming angles were used; directly from above to measure densities and with an angle to capture movement paths, interactions between participants and behaviour. The position of the cameras is reproduced in figure 3.3.

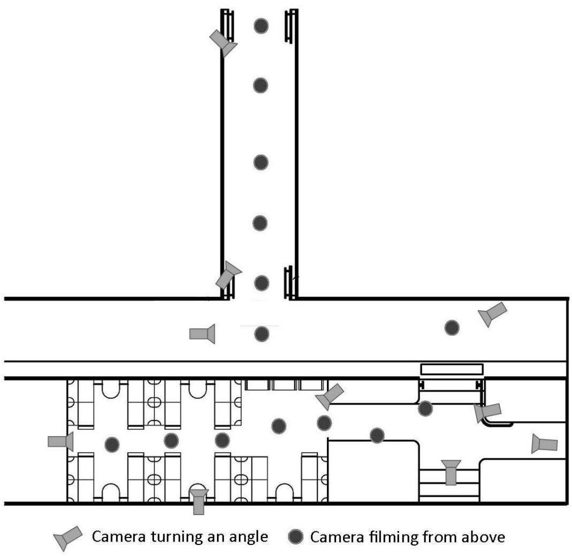


Figure 3.3: Camera position in the train and tunnel.

Ethics
Performing experiments with humans requires ethical considerations. None of the participants were exposed to any fire hazards such as smoke, heat or flames. Furthermore, all assistants and observers in the experiments had taken a course in first aid. All participants were guaranteed full anonymity and none of the recorded material is distributed to a third party. The project was notified and approved by the Danish Data protection agency and is notified to the National Committee on Health Research Ethics. However, the ethical application was not subject to assessment by the committee since the experiments are categorized as register-interview-questionnaire research and the participants were not exposed to any extra ordinary conditions. Even though the official ethical assessment system in Denmark do not consider the current experiments, the researchers followed an internal ethical codex develop at the Department of Civil Engineering at the Technical University of Denmark [PI-43]. All participants signed an informed consent before taking part in the experiment and were informed that they could withdraw at any time during the experiments.

Source of errors
In the current experiment the participants were only instructed in evacuating the train and tunnel in a safe way. They were not given any instructions about the warning not the egress path. In addition, the participants in the experiments took part in more than one exercise or replication, due to the limited number of test persons. It is therefore reasonable that the participants gained familiar with the test environment. Furthermore, they might have established some kind of a personal relationship to each other during the experiments. This personal relationship might have influenced the results because people might have been more willing to assist each other. The optimum setup of the experiments would have been to use each participant once.

The position of the cameras is also a source of concern. The cameras are mounted temporarily and it was required that they did not leave any marks on the existing structure. Furthermore, the cameras had a limited battery life and were changed between the second and third setup. These circumstances entail uncertainties that need to be accounted for in the analysis.

In a real situation the evacuation flow from the transversal tunnel would be affected by the evacuees' ability to distribute in the opposite tunnel. If the evacuees hesitate to distribute, congestion might occur in the transversal tunnel and thereby reduce the evacuation flow. In the experiments there was no opposite tunnel pipe and people were considered safe outside the tunnel and no congestion in the transversal tunnel were observed.

Results and discussion

The results, divided into parts, illustrate the evacuation process from the train in the tunnel to the safe place outside the tunnel. Firstly the reaction time is presented followed by walking speed descending the three steps from the train to the main tunnel. Thereafter the walking speed in the main tunnel and transversal tunnel is presented. Lastly, the total evacuation times are given and discussed.

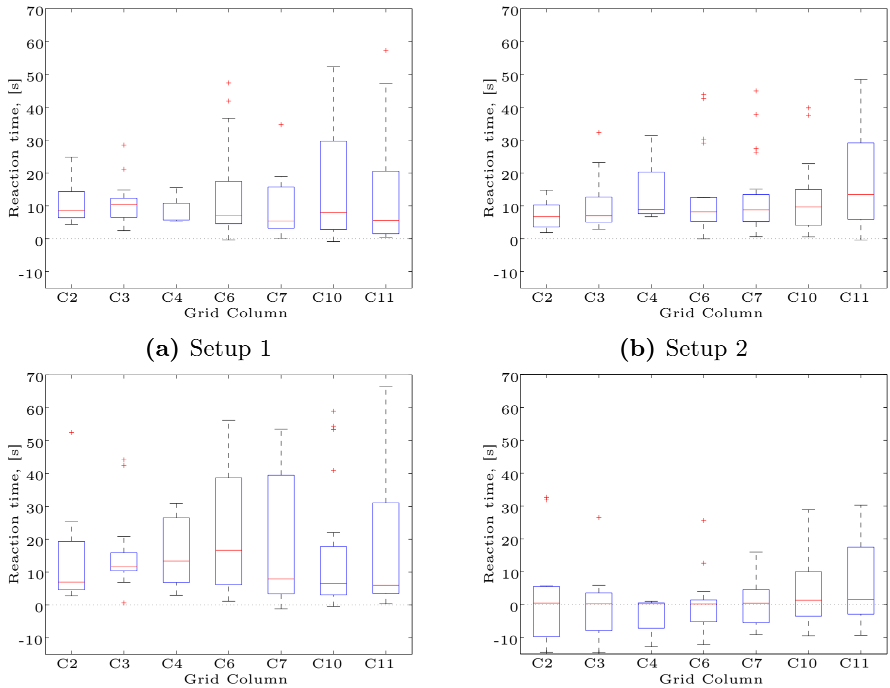
Reaction Time
The reaction time is often included in the reaction and decision time or pre-activity time. In the current study the decision time is was not accounted for since the participants are were instructed told to in evacuating the train by the given warning message . Thus, the reaction time is was studied separately, and is was measured as the time period from when the warning message ends until the participants raise from the seat and are were ready to walk and evacuate the train. The reaction time is was only measured for the seated participants. The tested hypotheses are:

- Participants closest to the exit rise first.
- Reaction times for participants in the same seating group are similar.

The reaction time was determined for the four setups with different composition of the test group, and is displayed in figure 3.4, as box plots a-d for the four setups respectively. The box plot gives the median for the reaction time, the edges of the 25th and 75th percentile, the 99.3 confidence interval and eventually outliers. The horizontal axis shows the grid column, and the vertical axis the reaction time in seconds. Each subfigure display seven boxes corresponding to the seated position in the grid, cf. figure 3.1. The higher the number of grid column the longer distance to the exit of the train carriage. Hence, C2 (grid column 2) is the one closest to the exit and C11 is the one furthest away from the exit.

The reaction times distributed on the seven columns for setup 1 are given in figure 3.4a. It is seen from the figure that the span in reaction time increases the further away from the exit a person is seated. The median values lies in the range from 5.4 s to 10.47 s whereas the mean reaction time for setup 1 is in the range from 8.23 s to 15.31 s according to table 3.2. The overall mean for setup 1 is 11.42 s. The statistical analysis shows that there are seven outliers.

In setup 2 there is a trend showing that the median values increase for the first three columns, then drops for column 6 and from there increases up to



(a) Setup 1 **(b)** Setup 2

(c) Setup 3 **(d)** Setup 4

Figure 3.4: Reaction time for the four different setups. C indicates the column in the grid referring to figure 1. The lower the number the closer to the exit door from the carriage. a: Setup 1 (without mobility impaired), b: Setup 2 (without visually impaired), c: Setup 3 (without children), d: Setup 4 (only able-bodied)

column 11. The range for the confidence interval illustrated by the extremes is likewise increasing for the C2 to C4, drops at C6 and then from there increasing up to C11. The span between the 25th and 75th percentile follow the same patterns as the median values and extremes. The statistical analysis carried out to create the box plot reveals 11 outliers for the current setup. The outliers are primarily observed for C6, C7 and C10. The number of outliers indicates a large spread between the reaction times observed for the specific columns. Regarding the mean reaction time for each column, it is seen from table 3.2 that the reaction time increases from C2 to C4 decreases for C6, C7 and C10 and jumps to a maximum value for C11. The overall mean reaction time is 12.02 s.

Subfigure 3.4c display the obtained reaction times for setup 3. For this setup it is not possible to detect a general pattern within the results. The median values go up and down in no specific pattern and the same goes for the whiskers. There is a tendency that the distance between the 25th and 75th percentile is largest for C6 and C7, the grid columns in the middle of the train carriage. The mean values lies in the range from 15.40 s up to 20.85 s with an overall mean of 17.4 s.

In the last setup, setup 4, negative reaction time is observed, see table 3.2. The negative times arise when a person is ready to move before the warning message has come to its end. It is chosen not to change the method of measuring the reaction to sustain the possibility of comparing the results for the different setups. The median values for the fourth setup with only able-bodied adults lies around 0. The smallest interval between the 25th and 75th percentile is found for C4 and C6. The small interval indicates that the spread among the reaction times are less than for the other grid columns. Again, a number of outliers are identified indicating that some people have a reaction time which does not lie within the confidence interval. Regarding the mean value for the reaction time, it is found that the participants in average are ready to evacuate after 2.37 s. The persons seated in column C3 and C4 are ready to move before the warning message ends. The participants seated furthest away from the exit have the longest reaction time.

The results for the reaction time are not sorted after subpopulation. The reaction time is solely based on the seated participants and since the participants are seated randomly there are not two equal runs. In addition, not all persons have been seated during the 20 replications of the experiment. Based on the results it is therefore not possible to conclude anything about the reaction time for a specific subpopulation, when dealing with heterogeneous groups. More homogeneous studies are needed to be able to draw conclusions on this matter. The outliers identified might be explained by the different characteristics of the subpopulations. In addition, it is found from the recordings that some participants by purpose stay seated until the train carriage is almost empty. It is assumed that this behavior is to reduce the time they have to wait standing and queuing to get out of the train carriage. Based on the results for the four setups it is not possible to confirm or deny the hypothesis that the participants seated closest to the exit from the carriage have the lowest reaction time, when dealing with heterogeneous groups. However, for the homogeneous group of able bodied people, it is seen, that the reaction time increases with distance.

The second hypothesis to test about the reaction times was if the reaction time was dependent on the other participants seated in the same seating group. The hypothesis is solely tested with quantitative measurements. The standard deviation (STD) within each seating group is found for all runs within each setup. The obtained values are then compared to the overall STD for all groups for each setup. Figure 3.5 a-d shows the obtained standard deviations.

Subfigure 3.5a display the STD of the reaction time for setup 1. From the

Table 3.2: Mean reaction times, $[s]$, for all grid columns with seated participants for each of the four setups.

	Setup 1 $[s]$	Setup 2 $[s]$	Setup 3 $[s]$	Setup 4 $[s]$
C2	10.51	7.22	18.88	2.02
C3	10.89	10.72	15.65	-0.66
C4	8.23	13.95	16.07	-3.29
C6	14.12	13.2	20.85	0.10
C7	9.17	12.78	18.59	1.16
C10	15.31	11.76	15.40	5.17
C11	12.4	18.09	18.15	6.93
Overall	11.42	12.02	17.40	2.37

figure it is seen that 5 points are situated above the overall STD for setup 1. Furthermore, 19 out of 29 data points have a STD of 5 seconds or less. Hence, there is a correlation between the STD for the reaction time and the seating group indicating that people are influenced by the people seated in the same seating group. For seating group 1, 2 and 6 none of the data points representing a value higher than the overall STD for the setup.

The STD for the reaction time in setup 2 is shown in figure 3.5b. Here it is seen that 6 points are placed above the overall STD for the current setup, and additional three points are close to the overall STD for the setup. There is 19 out of 29 points with a value equal to or less than 5 seconds. As for the first setup the results indicate a relation between the reaction time for the participants in the same seating group.

For the third setups the results are given in subfigure 3.5c. For this setup there are 8 data points above the overall STD for the setup. Furthermore, 13 of the 30 data points represent a value less than 5 seconds. The spread on the measured STDs are higher for setup 3 compared to the three other setups. Likewise the overall STD is between 54% and 73% higher compared to setup 1, 2 and 4. Hence, there could not be seen a relation between the reaction time for the participants in the same seating group.

In the fourth setup subfigure 3.5d, reveals that 4 STS for the reaction time is above the overall STD for the setup. It is found that 25 out of 30 data points have a value less than 5 seconds. This setup most clearly shows the STDs for the reaction time within the seating group is significantly less than the overall STD for the setup.

The overall tendency in the subfigures in figure 3.5 shows that the STD for the reaction times within each seating groups is generally lower than the overall STD in the same setup. Based on the obtained STD values it is concluded that there is a correlation between the reaction time for the persons within the same seating group.

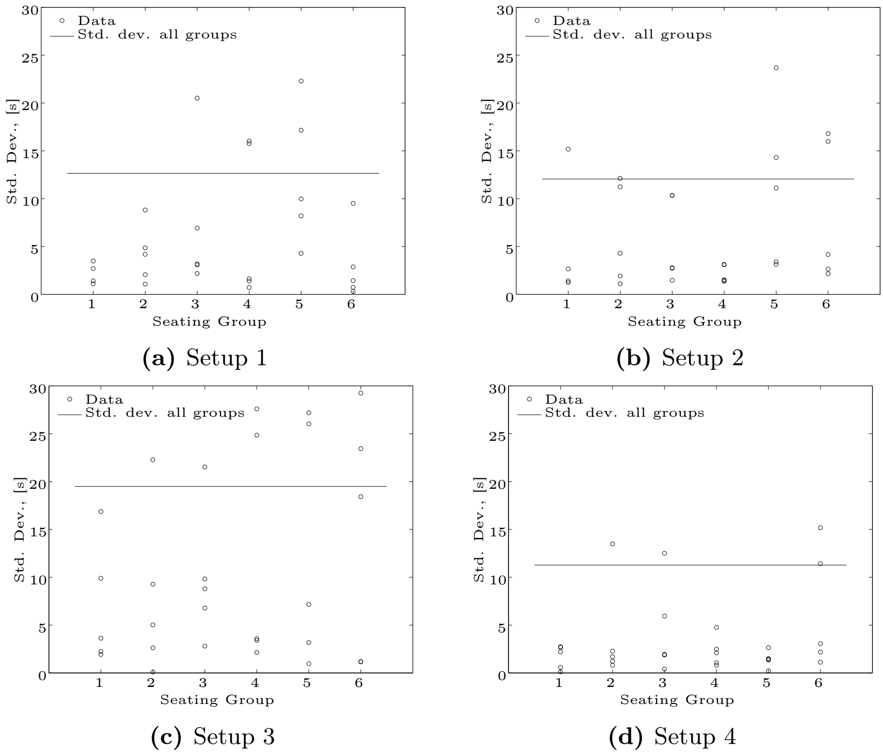


Figure 3.5: Standard deviation for reaction time within seating groups. The position of each seating groups is indicated in figure 1. Solid line indicates the overall standard deviation within each of the four setups. a: Setup 1 (without mobility impaired), b: Setup 2 (without visually impaired), c: Setup 3 (without children), d: Setup 4 (only able-bodied)

Walking speed descending stairs
There are three steps from the train to the platform. The walking speed is measured for this short descent, and the results are displayed in figure 6.4. The figure is divided into seven sub figures giving the results for each of the seven population groups. In each graph the data points are given together with a trend line for the data and the commonly used model developed by Nelson and MacLennan, hereafter called the N&M curve. The vertical axis represents the walking speed whereas the horizontal axis represents the density. The walking speed is measured from the moment a person lift his/her first foot from the floor and starts to bend in the opposite knee to reach the first tread until the

first foot is placed on the platform with all the body weight on that foot. The diagonal distance is 1.1 meter with a tread depth of 235 mm and riser height of 230 mm. The density is then measured as an average of persons on the stair in the same time period as it takes the studied person to descend the three threads. The area of the three treads is 0.875 m^2 and the lowest density with one person on the stair is therefore 1.14 $pers/m^2$. The literature gives a limit for the free walking speed at a density of 0.54 $pers/m^2$. In the current study there is not registered any densities in the range where individuals theoretically should walk freely. However, individuals are observed alone on the stair, but the area of the stair entail a density higher than 0.54 pers/m^2. Consequently, several data points with the same density corresponding to one person at the stair can be seen in figure 6.4 a-g.

The first sub figure, figure 3.6a, shows the result for the able-bodied subpopulation, who participated in the experiments. It is seen that the majority of data point are situated above the N&M curve. Likewise, the corresponding trend line is above the N&M curve. Comparing the slope and vertical intersection for the trend line and the N&M curve it is found that the slope is less steep but that the intersection point are in a range of 0.1 m/s. The different slopes indicate that the density dependency is not as dominant for the obtained compared to the N&M curve.

In figure 3.6b, the result for the elderly subpopulation is displayed. There is evidence of a higher concentration of data points for a density corresponding to 1.143 $pers/m^2$. That is due to the method used to determine the density. The trend line intersects with the N&M curve and the gradient is lower. This indicates a weak sign of a slight density dependence of the walking speed of this population. The intersection point with the vertical axis is displayed 0.3566 m/s downwards indicating a reduced free walking speed comparing with the N&M curve.

For the children figure 3.6c shows the obtained results. The slope of the trend line is nearly zero giving that the walking speed descending the three treads for the children participating in the experiments are not affected by the density. The almost flat trend line might be explained by the experimental setup with only three steps and sufficient space on the platform where the participants could distribute after the descend. The mean walking speed for the children can therefore be approximated by the intersection point with the vertical axis, which is 0.6236 m/s. Comparing the walking speed with the N&M curve it is seen that the free speed for the children are reduced by 28%. Even though the obtained results might not be representative, they indicate that there is a difference in the characteristic for the for test persons on which the N&M theory are based and the children taking part in the current study.

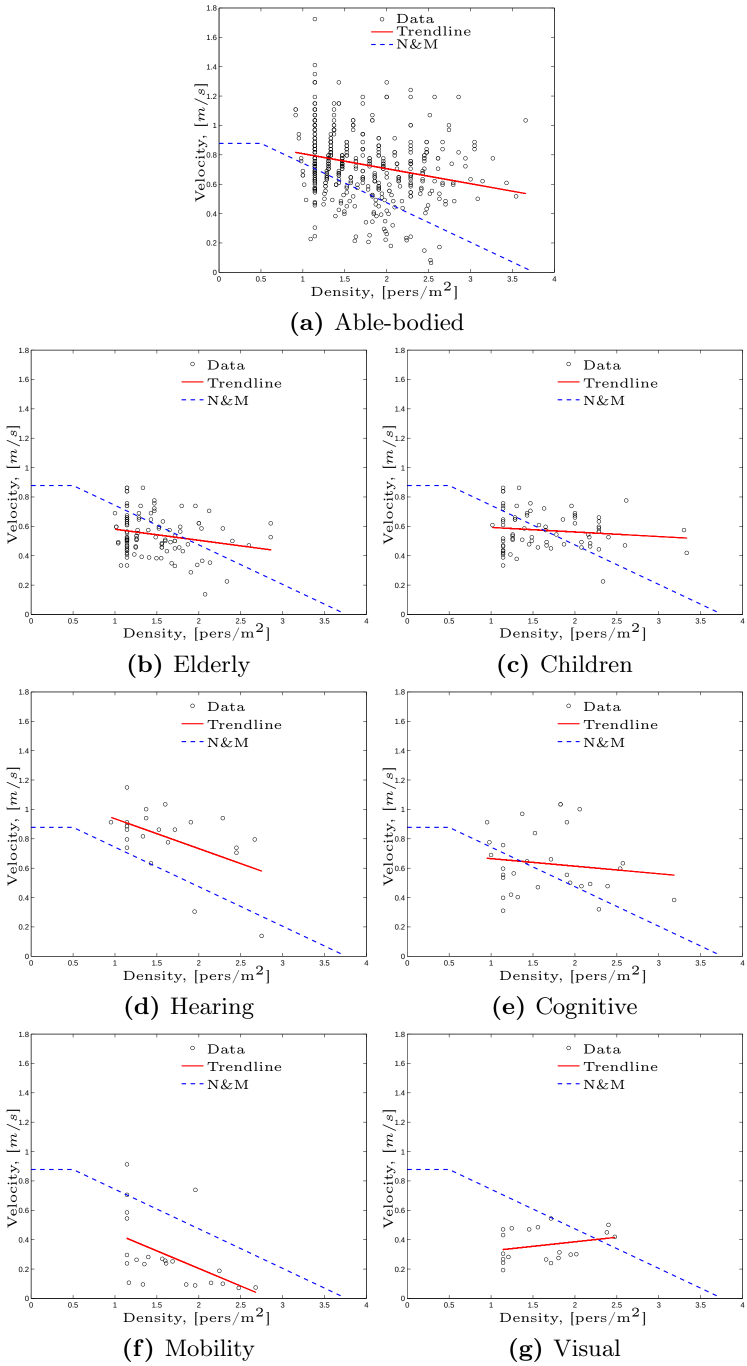


Figure 3.6: Walking speed descending stairs from train to tunnel platform.

Figure 6.4 is accompanied by table 3.3, which gives an overview of the coefficients for the trend lines and the N&M curve. The format of the trend line is ax+b where a is the slope and b is the intersection point with the vertical axis.

Table 3.3: Coefficients for trend line , ax+b, obtained for the different population groups and theoretical values given by Nelson and MacLennan descending stairs.

Group	a	b
Able-bodied	-0.102	0.91
Elderly	-0.075	0.66
Children	-0.031	0.62
Hearing	-0.204	1.14
Cognitive	-0.051	0.72
Mobility	-0.239	0.68
Visual	0.062	0.26
N&M	-0.269	1.01

The first sub figure, figure 3.6a, shows the result for the able-bodied subpopulation, who participated in the experiments. It is seen that the majority of data point are situated above the N&M curve. Likewise, the corresponding trend line is above the N&M curve. Comparing the slope and vertical intersection for the trend line and the N&M curve it is found that the slope is less steep but that the intersection point are in a range of 0.1 m/s. The different slopes indicate that the density dependency is not as dominant for the obtained compared to the N&M curve.

In figure 3.6b, the result for the elderly subpopulation is displayed. There is evidence of a higher concentration of data points for a density corresponding to 1.143 $pers/m^2$. That is due to the method used to determine the density. The trend line intersects with the N&M curve and the gradient is lower. This indicates a weak sign of a slight density dependence of the walking speed of this population. The intersection point with the vertical axis is displayed 0.3566 m/s downwards indicating a reduced free walking speed comparing with the N&M curve.

For the children figure 3.6c shows the obtained results. The slope of the trend line is nearly zero giving that the walking speed descending the three treads for the children participating in the experiments are not affected by the density. The almost flat trend line might be explained by the experimental setup with only three steps and sufficient space on the platform where the participants could distribute after the descend. The mean walking speed for the children can therefore be approximated by the intersection point with the vertical axis, which is 0.6236 m/s. Comparing the walking speed with the N&M curve it is seen that the free speed for the children are reduced by 28%. Even though the obtained results might not be representative, they indicate that there is a difference in the characteristic for the for test persons on which the N&M theory are based and the children taking part in the current study.

Figure 3.6d, shows the results for the hearing impaired subpopulation. The figure shows that all data points, except two are situated above the N&M curve. The trend line is hence, also positioned above the N&M curve. The slope of the trend line is in a range of 0.06 from the theoretical value. Comparing the intersection points it is found that the point for the trend line is 0.12 m/s above the intersection for the N&M curve.

The results for the cognitive impaired test persons are shown in figure 3.6e. The slope of the trend line is for this group almost zero, as for the children. This indicates that the walking speed descending the steps is not affected by the surrounding density. The intersection point with the vertical axis is 0.7162 m/s, which is 0.15 m/s less than the free speed prescribed in the literature [PI-44].

In figure 3.6f shows the results for the mobility impaired test group. It is seen that only two data points are above the N&M curve indicating a noticeable difference between the mobility impaired test group and the characteristics of the test group behind the N&M curve. The slope of the trend line is comparable with the slope of the N&M curve, but it is displaced downwards. The gap between the N&M curve and the trend line is explained by the difference in the intersection point with the vertical axis. The intersection point for the trend line is 0.33 m/s lower compared to the N&M curve.

The last subfigure, figure 3.6g, displays the result for the visually impaired participants. The majority of the data points are situated below the N&M curve, showing that the walking speed is lower than the value prescribed by the theory. Furthermore, this figure shows the first trend line with a positive slope. A positive slope indicate that the walking speed increase even though the density is increasing. This trend is unusual and need to be investigated further, before a final conclusion can be drawn. . However, previous studies of density independence of this population have been conducted, [PI-32]. Here it was found that visually impaired individuals were able to maintain a higher walking speed even though the density was increasing. The trend was however not as strong as found in the current study.

Walking speed in main tunnel
The horizontal walking speed is divided into two parts - the walking speed in the main tunnel and in the transversal tunnel. As for the walking speed descending

stairs the results are displayed for each subpopulation, and the walking speed is given in the vertical axis whereas the density is represented by the horizontal axis.

The walking speed in the main tunnel is determined based on two check points with an internal distance of 2 meters. The check points are positioned so that the transitions from the train to the main tunnel and the 90 degree turn into the transversal tunnel does not affect the walking speed. The density is then measured as the average number of persons in the area between the checkpoints in the same time period as it takes the studied person to travel between the two check points divided by the floor area between the two points. The results for the main tunnel are displayed in figure 3.7 a-g. In each of the sub figures the data points are presented together with a trend line and the N&M curve. The coefficients for the trend lines are given in table 3.4.

Figure 3.7a gives the results for the able-bodied adults. Here it is seen that the data points are evenly distributed around the N&M curve. In addition, the slope of the trend line is comparable with the slope of the N&M curve with a difference on the third decimal. The intersection point with the vertical axis is 0.05 higher for the able-bodied compared to the N&M curve. This difference is seen as the small displacement of the trend above the N&M curve. The obtained walking speed in the main tunnel for the able-bodied subpopulation confirms the N&M theory.

In figure 3.7b, the results for the elderly population are displayed. It is seen that the majority of data points is situated below the N&M curve. The coefficients of the trend line show that the slope is 0.35 steeper for the trend line compared to the N&M curve. The intersection point with the vertical axis is 0.08 lower for the trend line compared to the N&M curve and the trend line is then displaced downwards. The data points are localized evenly around the trend line without any outliers. This indicated that the older persons within this group are walking similar between the two checkpoints in the main tunnel.

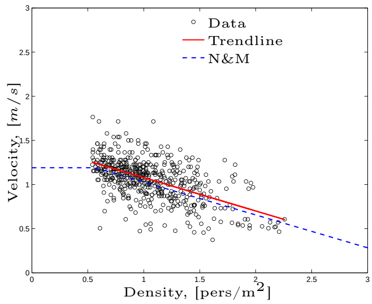
The walking speed for the children is showed in figure 3.7c. Here it is seen that the spread between the data points are larger than for able-bodied and older people. This indicates that the children participating in the experiment have more uneven walking characteristics. The amount of data points above the N&M curve is larger than below that curve. This is also reflected in the trend line, which is positioned above the N&M curve. However, the slope is similar to the N&M curve with a small difference of 0.011. The walking speed is therefore affected by the density in the same manner as for elderly and able-bodied persons. The difference is implied by the difference in free speed expressed by the intersection with the vertical axis.

The relation between walking speed and density for the hearing impaired participants are displayed in figure 3.7d. The pattern described for the three previous sub-populations is changed for this group of people. The amount of data points are less, because of a maximum of three hearing impaired persons participating at a time. Likewise, the trend line intersects with the N&M curve and has a slope which is steeper. The intersection point with the vertical axis is at 1.65 resulting in a difference of 0.25 m/s comparing with the N&M curve. The differences observed for the hearing impaired participants show that this group is more affected by the density than the able-bodied and elderly persons and the children.

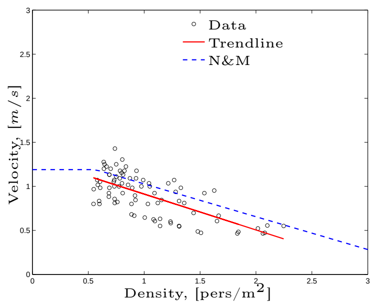
The next sub-figure, figure 3.7e, gives the results for the cognitive impaired subpopulation. The results for this group is uneven distributed with a big difference between minimum and maximum. Comparing the trend line with the N&M curve shows that the trend line is displaced upwards and the slope is 0.08 less steep. This implies that the cognitive impaired participants has a higher free speed, but is affected more by an increasing density.

Looking at the mobility impaired participants figure 3.7f shows that all data points is situated below the N&M curve and is evenly distributed. The trend line has a slope which is comparable with the N&M curve but is 0.036 less steep. The intersection point with the vertical axis 0.36 lower than for the N&M curve indicating that this subpopulation has a lower free walking speed than prescribed by the theory developed by Nelson and MacLennan.

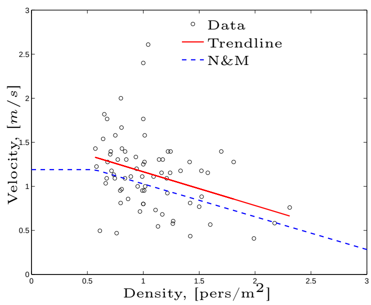
The last subpopulation is the visually impaired participants. The results for their walking speed dependent of density are showed in figure 3.7g. Here it is seen that the data points are evenly distributed with the majority of points below the N&M curve. The trend line is significantly different compared to the others obtained from the other sub-populations in the main tunnel. The slope is very flat with a value of -0.101 which is a difference of 0.271 to the slope of the N&M curve. The intersection with the vertical axis is 1.01 m/s which imply a lower free walking speed compared to the theory. The flat trend line indicates that people with visual impairment are less affected by density compared to the other sub-populations.



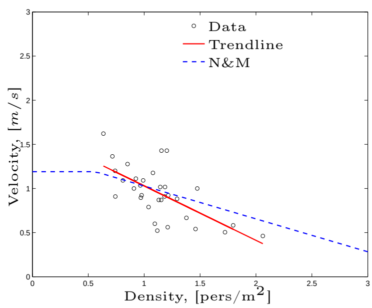
(a) Able-bodied



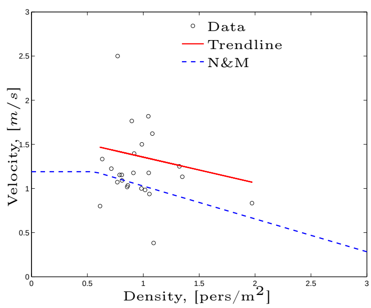
(b) Elderly



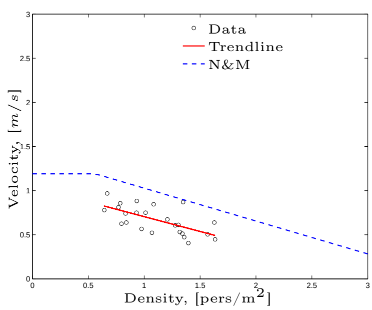
(c) Children



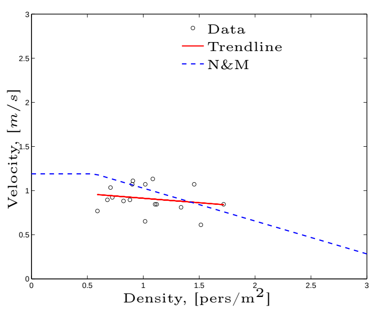
(d) Hearing



(e) Cognitive



(f) Mobility



(g) Visual

Figure 3.7: Walking speed in main tunnel (horizontal plane).

Table 3.4: Coefficients (y=ax+b) for trend lines obtained based on walking speed in main tunnel.

Group	a	b
Able-bodied	-0.378	1.46
Elderly	-0.407	1.32
Children	-0.383	1.55
Hearing	-0.617	1.65
Cognitive	-0.292	1.51
Mobility	-0.336	1.04
Visual	-0.101	1.01
N&M	-0.372	1.40

The highest density observed in the experiments in the main tunnel was 2.3101 $pers/m^2$ obtained for the children. This density is categorized as a medium density. Low densities are up to 1 $pers/m^2$, medium densities from 1 $pers/m^2$ up to 2.5 $pers/m^2$ and high densities higher than 2.5 $pers/m^2$. The obtained trend lines might therefore be different if high densities had occurred in the experiment.

Walking speed in transversal tunnel
The second part of the horizontal walking speed is determined for the transversal tunnel. There was established seven check points along the transversal tunnel. The walking speed and the density where measured between each of the seven points, resulting in six pairs of values for each person. The amount of data for the transversal tunnel is therefore larger than for the main tunnel, where there only was two check points.

The results for the transversal tunnel are presented the same way as for the main tunnel with a sub-figure for each of the seven sub-populations, see figure 3.8 a-g. In each sub-figure the data points are given together with a trend line and the N&M curve. The coefficients for the trend lines are given in table 3.5.

The first subpopulation is able-bodied adults and the results are presented in figure 3.8a. It is seen from the figure that a large portion of the data points lies below the N&M curve and this is supported by the trend line, which is likewise positioned below the N&M curve. The slope for the trend line is -0.468, which is 0.096 steeper than for the N&M curve. The main difference between the two lines are the intersection point with the vertical axis where there is found a difference of 0.1241.

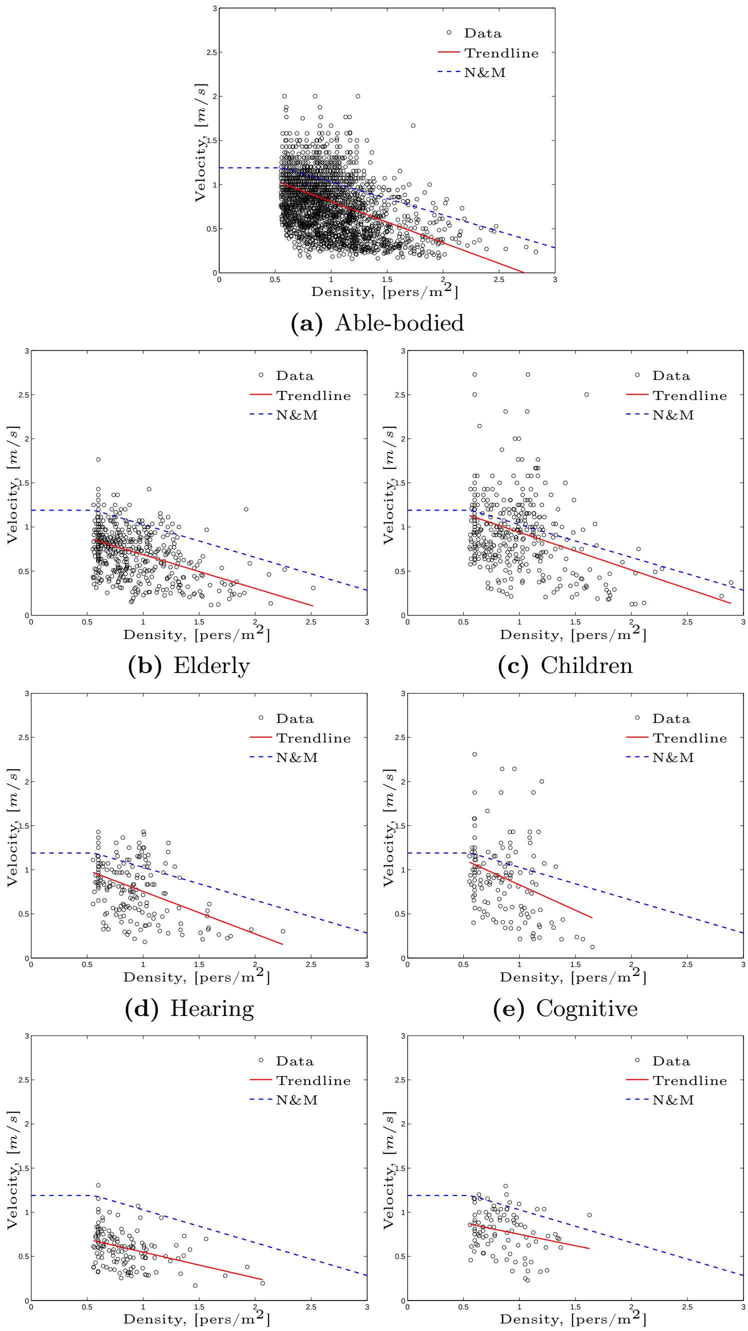
The picture is the same for the elderly subpopulation where the results are showed in figure 3.8b. For this group of people the majority of the data points are situated below the N&M curve. The slope of the trend line is almost similar to the one for the N&M curve, but the difference is found in the intersection point with the vertical axis. The intersection point for the trend line is 1.0696 compared to 1.4 for the N&M curve. This results in a difference of $0.33 m/s$. If the obtained trend line is general for an elderly population there would not be observed any movement at a density of 2.79 $pers/m^2$.

Figure 3.8c displays the relation between walking speed and density for the children. There is seen a large spread between the data points where the highest walking speed is 2.7278 m/s and the lowest is 0.1245 m/s. The trend line is situated slightly below the N&M curve with a slope of -0.4266, which is 0.0546 steeper than for the N&M curve. The intersection point with the vertical axis is 1.3665 which illustrates the parallel displacement downwards compared to the N&M curve.

In figure 3.8d the results for the hearing impaired participants are presented. It is seen from the figure that the main part of the data points lies below the N&M curve. The slope of the trend line is steeper compared to the N&M curve, which indicate a larger dependency of the density on the walking speed compared to the theory of Nelson and MacLennan. The point of intersection with the vertical axis is in addition lower than for the N&M curve which indicates a lower free walking speed for this segment of the population. However, the walking speed is in the current configuration is influenced by several parameters and not only the hearing impairment.

Figure 3.8e shows the results for the cognitive impaired subpopulation. There is seen a large variation in the walking speed, which demonstrate the differences among the individuals participating in the experiments. The trend line has a steeper slope compared to the N&M curve, implying that the density affects the walking speed in a higher degree than suggested by the N&M theory. The intersection point with the vertical axis is almost the same as for the N&M with a difference of 0.0044, which is considered negligible.

The result for the mobility impaired subpopulation is presented in figure 3.8f. Only two data points are situated above the N&M curve showing that this subgroup has a general lower walking speed compared to the theoretical N&M curve. The intersection point with the vertical axis is 0.8402 corresponding to a reduction of 40% compared with the N&M curve. This is a strong indicator for the difference in movement characteristics of different segments of the population. Comparing the slope with the N&M curve, it is found that there is a difference of 0.0795, and the trend line has a less steep curve. The difference is considered small and the density affects the walking speed regardless of the mobility impairment.



(a) Able-bodied

(b) Elderly

(c) Children

(d) Hearing

(e) Cognitive

(f) Mobility

(g) Visual

Figure 3.8: Horizontal walking speed in transversal tunnel.

Table 3.5: Coefficients (y=ax+b) for trend lines obtained based on walking speed in transversal tunnel.

Group	a	b
Able-bodied	-0.468	1.28
Elderly	-0.383	1.07
Children	-0.427	1.37
Hearing	-0.481	1.24
Cognitive	-0.576	1.40
Mobility	-0.293	0.84
Visual	-0.259	1.01
N&M	-0.372	1.40

The relation between walking speed and density for the visually impaired participants are displayed in figure 3.8g. The results show that only a small portion of the data points is situated above the N&M curve. The trend line is less steep compared to the N&M curve and the intersection point with the vertical axis is positioned 0.4 m/s lower. This indicates that the visually impaired participants have a lower walking speed compared to the N&M theory and that their walking speed are less affected by the density.

The general result for the relation between the walking speed and the density in the transversal tunnel is that all trend lines for the seven subpopulations are situated below the N&M curve. The slope of all the trend lines are negative and lies in a range of +0.2036 to -0.1133 from the value given by Nelson and MacLennan. The N&M curve are based on results from experiments that were carried out more than 30 years ago and where the test group mainly consisted of healthy and fit adults. It might therefore be questionable if it is realistic to compare the results from the current experiments with the N&M curve. However, the N&M curve is commonly used among engineers to calculate and determine the evacuation times from buildings and other structures.

Comparing the results from the main tunnel with the transversal tunnel, it can be seen, that the trend lines are shifted to the left, expressed by lower densities. The differences can partly be explained by the way the density is calculated and partly by human factors. Accordingly, the walking speed seems not only to be affected by characteristics based on subpopulation but also configuration of the experimental layout and human behavior. The density calculations are based on a reference area of same size, but with a different physical representation. Calculations show that the shift to the left for the results in the transversal tunnel is in the range from 0.19 $pers/m^2$ to 0.85 $pers/m^2$ with a mean of 0.53 $pers/m^2$. Applying this translation to the data from the transversal tunnel gives a better agreement between the results from the two tunnel sections. Manipulating the tunnel layout could enable the same physical representation of the reference area, but that would not be representative for an evacuation in a tunnel. Consequently, it is suggested that further investigations should be performed to quantify how much the sight and viewing angle influences the relation between walking speed and density. These results indicate that the density seen ahead by the evacuee should be weighted larger than the density outside the viewing angle. Furthermore, the participants did not overtake each other in the main tunnel. Overtaking was mainly observed in the transversal tunnel. The geometrical restrictions were likewise a factor that influenced the ability to overtake.

Total evacuation times
The total evacuation time was measured for all five runs within each setup and the average total evacuation time for each of the four setups is given in table 3.6. It is seen from the table that the total evacuation time for the first three setups with a mixed population is substantially higher compared to the group only with able-bodied people. The obtained values show that the total evacuation time is doubled for a mixed group compared to a homogeneous group. The standard deviation is likewise displayed in table 3.6, and the total evacuation time and the std. dev. combined shows that the time range for the three heterogeneous groups overlaps each other. It is therefore not possible to give a precise evaluation of which one of the compositions is faster or slower than the others. The time range for the mixed and the homogeneous group do not overlap, which underlines the difference between having a mixed and homogeneous group.

This result clearly shows that it is important to consider the composition of the population while designing fire safety and evacuation from buildings and other structures. In addition, it shows the importance of this study. In order to account for the subpopulations while performing calculations and assumptions for the evacuation, it is necessary to have available information about the evacuation characteristics of these subpopulations.

Table 3.6: Total evacuation times for the four different setups. Setup 1 (without mobility impaired), Setup 2 (without visually impaired), Setup 3 (without children), Setup 4 (only able-bodied)

Setup	Total time,[s]	Std. dev, [s]
1	88.69	9.5
2	103.08	13.75
3	108.53	3.94
4	50.15	7.92

The total evacuation times obtained in the current study cannot be used as a guideline for what times can be expected from a train in a tunnel since the time is very dependent on the configuration. However, the times obtained in these experiments indicates that there is a significant difference between a homogeneous group of able-bodied adults and a mixed group containing children, able-bodied, elderly and people with different impairments.

Conclusion

The current paper primarily deals with evacuation characteristics of people from a train in a tunnel. The effect of heterogeneity and accounting for people without regard of age and impairment on the evacuation is described. The study has a series of findings on the reaction time inside the carriage, walking speeds on stairs, in the main- and transversal tunnel, as well as the total individual evacuation times.

For the homogeneous group, the able-bodied group, it was seen that the reaction time increases the further away from the exit a person was seated. Based on the results it was not possible to conclude anything about the reaction time for a specific subpopulation in the heterogeneous mixtures. Some participants chose to remain seated in the train until the carriage was almost empty.

There was found a correlation for the reaction time for the persons within the same seating group. Previous research and experiments have shown that people look to others to help them in the decision-making process [PI-45]. In addition, it was found that the normative social influence is strongest among people that acts in a group formation compared to people acting individually [PI-46]. The correlation between the reaction time and the seating group might be caused by the social influence among the participants in the same seating group. The difference in reaction times within and between the seating groups might be explained by group behavior; the possibility to visually observe participants sitting in other groups.

Descending the stairs from the train to the tunnel, it was found that the N&M curve is conservative compared to the curves of the able-bodied and the hearing impaired population. The density dependency for the able-bodied people was not as dominant for the obtained results compared to the N&M curve. There was a varying density dependence of the walking speed of all groups except the visual impaired population.

The obtained walking speed in the main tunnel for the able-bodied subpopulation confirms the N&M theory. The N&M curve is conservative for the populations: able-bodied, children and cognitive impaired. Most children have an age of 6. Other studies show, that the N&M curve is not conservative with respect to walking speed of children at all ages [PI-47]. The walking speed is affected by the density in the same manner as for elderly and able-bodied persons. The cognitive impaired participants have higher free speeds. The walking speed of all populations is affected by increasing densities. However, the walking speed of people with visual impairments are least affected be increasing density. The highest density was 2.31 $pers/m^2$ and was attained by the children in the main tunnel. However, there are indications of that the degree to which the walking speed is affected by the density is affected by the sight and how many people can be identified in a person's point of view.

The total evacuation time for the first three setups with a mixed population is significantly higher compared to the group only with able-bodied people. The obtained values show that the total evacuation time is doubled for a mixed group compared to a homogeneous group.

These results show that it is important to consider the composition of the population while designing fire safety and evacuation from buildings and other structures. In addition, it shows the importance of this study. In order to account for the subpopulations while perform calculations and assumptions for the evacuation, it is necessary to have available information about the evacuation characteristics of these subpopulations.

Acknowledgement

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Chapter 4

Evacuation Safety for Everyone? A study on access and egress of people with impairments

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Thesis Paper	II
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	A study on Access and egress of people with impairments
Author:	J.G. Sørensen and A.S. Dederichs
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Abstract

Members of the vulnerable part of the population such as people with disabilities more likely suffer in fires compared to able-bodied adults. This and the demand on accessible building design makes it of high concern to place a focus on the fire safety provided in buildings for this group of people. The objective of this study is to identify which type of buildings vulnerable people are accessing in their everyday life to ensure equal possibilities for evacuation during an emergency, and to assess their experiences during a possible evacuation. An interview survey is carried out during a full-scale evacuation exercise with a test sample containing elderly people, and people with four different types of impairment, who are considered vulnerable during an emergency. The interview is based on a questionnaire containing a range of open and closed questions. The results show that the vulnerable group experienced different difficulties dependent on their type of impairment and age. The results also reveal that people with limitations visit shopping facilities, transport terminals, and sport facilities on a daily or weekly basis. In addition, it is identified that building elements to traverse from one floor to another create problems for this segment of the population. The vulnerable part of the population visits almost all kind of buildings, and they therefore needs to be considered in the safety design of any building to ensure a sufficient safety level for this group of people.

Introduction

This paper is the second in a series describing the evacuation characteristics of heterogeneous populations. The first paper presents the quantitative results regarding walking speeds and evacuation times obtained in the experiments involving mixed populations, accounting for people of a wide age range and different impairments. A background on vulnerability, fire safety legislation and evacuation in tunnels are given in the first paper. This second paper will present the qualitative results from the experiments, which included an interview study with the vulnerable part of the test group.

Social quality is one factor used in assessing the sustainability of a building design [PII-1]. Here, all users of a building should have equal possibilities to apply the functionality of the building and thereby avoid discrimination of certain segments of the population. For a sustainable building design, the aspect of social quality of the design is deep seated in the design and establishment of a building. In the context of fire safety design social quality can be defined in enabling equal egressibility; avoiding a design, which disable parts of the population from participating in an evacuation, leaving them to be rescued by the rescue service in a later stage of the fire.

The egressibility of different designs in the context of evacuation for elderly people and people with disabilities has been carried out [PII-2 - PII-4]. The focus of the experiments was evacuation from trains. The horizontal gap between train and platform has been shown to be best being 2x2cm [2]. The vertical gap height has been shown to be limited for elderly people at heights above 35 cm [3] and above 64 cm for able-bodied people evacuating in smoke [PII-4]. Furthermore, it could be shown that evacuation time increases with the height between car and platform [PII-5].

Another parameter to enhance social quality is accessibility to buildings, which is a requirement stated by law in many countries [PII-6 - PII-7]. Accessibility is one main component of Universal Design [PII-8]. This has led to a decrease in handicap generating building designs and enables a larger diversity of visitors for different types of buildings. It may be assumed that an increased accessibility of the building design leads to an increase in visits of disabled people in different building types. People with disabilities participate in a range of activities able-bodied people do and leave their homes in a high degree [PII-9]. However, the questions posed in the present study are: What building types are visited by people with disabilities, and what difficulties they experience with building designs. These questions are asked in an interview survey carried out during a full-scale evacuation exercises from a train in a tunnel. In addition to the questions about use of different building types, the participants' experience with the evacuation exercise was evaluated. The experiments and the interview survey were conducted in May 2012 in Denmark. The aim of the study was to identify building types visited by members of the vulnerable part of the test sample and evaluate their experience during the evacuation exercise. In this study the vulnerable part was considered as elderly people, and people with four different types of impairments namely reduced mobility, hearing, vision, and cognitive impairments. Able-bodied adults and children also participated in the evacuation exercises however these two groups are excluded from the study. The evacuation exercise was conducted from an IC3-train in a test tunnel corresponding to a section of the Great Belt rail tunnel connecting Zealand and Funen in Denmark. The method of the investigation is described in the following, where also the experiment, questionnaire/interview and characteristics of the participants are described. The results of the study are then presented, discussed and conclusions are drawn.

This paper contributes with an analysis of the qualitative results mainly results from the interview survey conducted as a part of the full-scale experiment from a train in a tunnel.

Methodology

The overall frame for this study is the evacuation experiment performed from a train in a tunnel. The train in the tunnel was an IC3-train with a capacity of 23 seated and 13 standing passengers in the carriage, and additional 10 standing passengers in the entrance lobby between the carriage and the exit door. The total number of passengers was 46 in total for each exercise, corresponding to a crowded train. The evacuation exercises were initiated by a spoken warning message from the central communication system telling that smoke was observed outside the train, and that passengers should evacuate immediately. The egress path led from the train to the main tunnel using the ordinary train exit with three steps, and from there to the nearest transversal tunnel to reach the outside of the tunnel, which was considered a safe place. The longest distance to the safe place outside the tunnel was 24.5 meters. Before each exercises the participants were assigned specific seats and positions in the train. The seating was determined randomly prior the exercises.

The test population was selected to match as closely as possible the demographic profile of the Danish population, including able-bodied adults, elderly people, children, and people with different types of impairments (mobility, hearing, vision and cognitive impairments). The characteristics of the participants are displayed in Table 1.

Table 4.1: Number of participants taking part in the evacuation exercise.

Subject group	Number of participants
Able-bodied people (A)	48
Children (<14) (C)	25
Elderly People (>65) (E)	12
Visually impaired people (V)	2
Hearing impaired people (H)	3
Cognitive impaired people (Co)	4
Mobility impaired people (M)	3

Participants were recruited from organizations for disabled people, the local community and other interest organizations. The evacuation exercise was conducted four times, each time with variations in the composition of the test population. The four exercises with different compositions were replicated five times, and in total 20 experiments were carried out. Data was recorded using temporarily installed video cameras. The data analysis included detection of behavioral patterns e.g. interactions between evacuees, and physical evacuation characteristics such as walking speeds, densities and flows. The quantitative results are presented in the paper "Evacuation safety - for everyone? A quantitative study on a train-tunnel experiment accounting for vulnerable people" written by Soerensen and Dederichs.

Interview survey
The interview survey was based on a questionnaire containing a range of open and closed questions. The vulnerable test sample consisted of 24 people according to Table 1 (excluding children). It was voluntary to take part in the interview survey and nine participants agreed to take part. This corresponds to 37.5% of the vulnerable test sample. The composition of the survey group is shown in Table 2. Out of the nine respondents four were using some kind of assistive technology. One respondent with mobility impairment used crutches and the other had an artificial lower leg. The two visually impaired respondents used a white can. The elderly respondents and the hearing impaired respondents did not use any aid. The use of aids is an important factor as it might influence the experience of the evacuation exercise.

Table 4.2: Number of participants taking part in the evacuation exercise.

	Elderly	Mobility	Hearing	Vision	Cognitive	Total
Test population [pers.]	12	3	3	2	4	24
Survey Population [pers.]	3	2	2	2	-	9
Percentage in survey [%]	25	66.6	66.6	100	0	37.5

The interview was divided into three parts. In part one the respondent's age, gender, type of impairment, and any aids used were clarified. The second part of the interview dealt with evaluating the egress from the train and tunnel. Both factual and more emotional questions were posed, and respondents were asked about their experience with the evacuation exercises. An example of a factual question was "What was your position in the train at the start of the exercise?", whereas an example of an emotional question was "How did you feel during the exercise both psychologically and physically?". In the third and last part of the interview the access and use of different building types was investigated. The everyday use of different types of buildings was investigated, the frequency of use, and any difficulties the respondents experienced during use of these types of buildings. To ensure respondents had good recall of the exercise, they were interviewed on the same day and at the same location as the evacuation experiments took place. The same interviewer carried out all interviews; this was to ensure consistency in the way the questions were asked and how the interviewer dealt with questions from the respondents. During the interview session the interviewer filled in the questionnaire and added notes. Furthermore all interviews were audio taped for documentation and to uphold the possibility for citing respondents.

Ethical Considerations
Ethics were considered in this study as the experiments involved human beings. In Denmark there are two relevant authorities - The Danish Data Protection Agency and the National Committee on Health Research Ethics. The current study was notified and approved by the Danish Data Protection Agency and general terms for data processing were given. In general, an ethical committee should approve all experiments, involving human beings or biological material. In Denmark there are however exceptions when studies or projects are categorized as register research, questionnaire-based projects or interview examination and do not incorporate any biological material [PII-10]. An application for approval by the Danish ethics committee was submitted. It was found that the current study did not need approval by the committee in Denmark, since it was categorized as register research and interview examination and did not include any biological material. In Denmark register research is defined as structured collection of data regarding individuals which is symbol-based including numbers and letters. Nor were the participants exposed to any fire hazards or extraordinary conditions such as smoke, heat or flames. Since no formal approval of the study was needed the authors develop an ethical codex inspired by common practice in other countries. Fulfilling the internal codex entailed that all participants was required to fill in an informed consent before they were allowed to take part in the experiments. The reason for the informed consent was that health related data can be processed from the video recordings, and to ensure that the purpose of the experiments was clear for all participants. Participation was likewise on an entirely voluntary basis and participants could withdraw at any time.

Results and Discussion

The results from the study were divided into two parts. The first part examines the participants' experience with the evacuation exercises. The second part evaluates the participants' use of different building types.

Evacuation exercise
One part of the interview study assessed the respondents' experiences during the evacuation exercises. The respondents' were asked to evaluate different stages of the evacuation, specifically perception of the alarm and movement to the safe place. The level of difficulties experienced in the different stages of the evacuation was evaluated on a five-level Likert scale with response options 1-5, where 1 were no difficulties, 2 minor difficulties, 3 medium difficulties, 4 large difficulties, 5 major difficulties. The results concerning perception of the alarm and movement are displayed in Table 3, respectively.

The results show that the elderly people did not experience difficulties (score 1) perceiving the warning message and act upon the alarm. Neither did they find it difficult to leave their start position. In addition, the mobility and visually impaired participants did not experience any difficulties (score 1-1.5) in understanding the alarm or respond to it. However, they reported minor difficulties (score 2.5) to leave their starting position. Contrary, it was very difficult (4.5-5) for the hearing impaired participants to perceive the warning message and respond based on it. The cause of the major difficulties for the hearing impaired was expected, since there was only verbal warning. The perception of the alarm is an important factor in relation to the reaction and decision time, which is a part of the total evacuation time. In many cases, it is observed that the reaction and decision time is a significant contributing factor to the total evacuation time, as it varies from seconds up to approximately half an hour dependent on the circumstances (i.e. alarm type, type of occupancy, type of fire etc.) [PII-11]. In the current study, it is shown that perception of the alarm and experienced difficulties were dependent on type of impairment and age. Only the hearing impaired respondents' recognized difficulties to understand and respond to the alarm because only verbal warning was used. The verbal warning could be supplemented with a visual warning (e.g. flashing lights) to ensure warning of hearing impaired people. However, training in the purpose of the visual lights and the general evacuation procedure is important. The different difficulties in perception of the alarm show that the type of alarm is important to consider while designing the safety system of a building. It is similarly important to ensure that everyone in the building is able to recognize the alarm and subsequently take action.

Regarding movement from the starting position, the experienced difficulties were from "no difficulties" to "minor difficulties", dependent on the group. The respondents who experienced the largest difficulties were mobility and visually impaired respondents. Difficulties in leaving the starting position might influence the rest of the evacuation flow, as queuing might occur behind the person with difficulties. Although, it is suggested that the layout of the train and conditions of the seats affected the experienced difficulties to leave the starting position because the seats were very soft due to bad suspension. Furthermore, the height of the seats was low. The experience of the end-user is an important factor to consider while evaluating the safety level of a building or structure, [12]. If the end-users' experience uncertainty during an emergency, they might get the impression that the building is not sufficiently safe, although the safety level is proven appropriate according to current regulations and guidelines.

Table 4.3: The experienced difficulties of different stages of the evacuation exercises evaluated on a 5-point link with response options 1 to 5, where 5 were very difficult.

Task	Mobility	Hearing	Vision	Elderly	Total
Perception of Alarm					
Understand alarm	1	5	1.5	1	2.1
Response to alarm	1	4.5	1	1	1.9
Leave stating position	2.5	1.5	2.5	1	1.9
Average	1.5	3.7	1.7	1	2.0
Movement					
Passing through automatic door	1	1	1	1.3	1.1
Passing through corridor	1.5	1	1	1	1.1
Use the stair to exit train	3	1	2	1	1.8
Choose direction after exiting the train	1	1.5	1	1	1.1
Find the transversal tunnel	1	1	1	1	1
Move in the transversal tunnel to safe place	1.5	2	1	1	1.4
Average	1.5	1.3	1.2	1.1	1.3

Movement to the safe place was divided into parts corresponding to the layout of the train and tunnel. The respondents' were asked to evaluate the parts chronologically starting with passage of the automatic doors from the carriage to the entrance lobby, to the travel through the transversal tunnel to the safe place outside the tunnel. Generally, it is seen from Table 3 that most participants' found movement to a safe place easy (score 1-1.5). The mobility and visually impaired respondents identified respectively minor and medium difficulties to traverse the three steps from the train to the main tunnel. The mobility impaired respondents with the artificial lower leg did not use any additional aid, but benefitted from the handrail and door pole to descend the steps. The respondents using crutches relied on assistance from fellow participants to traverse the steps from the train to the tunnel platform and reported major difficulties. Regarding the visually impaired participants the difficulties can be addressed by the identification of the first tread. It is seen from the recordings that they use their feet to search for the edge. It is likewise seen from the recordings that the visually impaired people were a bit reluctant to pass the last step to the floor in the main tunnel due to a gap of 70 mm. The recordings also revealed that mobility and visually impaired participants relied on help from fellow participants. None of the groups reported difficulties to choose their direction and find the transversal tunnel. However, the visually impaired and mobility impaired respondents identified minor difficulties to move in the transversal tunnel. Based on the interview recordings one hearing impaired respondents answered that he experienced medium difficulties (3) in the transversal tunnel due to the width of the tunnel section and that the high number of people made him feel affected by the movement of the crowd. The only correlation that was found between the time it took to complete a specific element of the egress path and experienced difficulty was for the mobility impaired respondents that used crutches. He experienced major difficulties (5) to traverse the steps from the train to the tunnel and time vice he used between 2 and 10 times as much time to complete the steps compared to the other respondents in the study.

Besides the interview study that revealed the respondents experience with the evacuation exercise, interactions between evacuees were registered during the exercises. Along the egress path observers were present. The position of the observers was in the train carriage, in the entrance lobby, in the main tunnel, and in the transversal tunnel. In 87 cases it was registered that a participant was lending a helping hand to a fellow participant. It is therefore considered a common behavior during the exercises. In addition, there were registered 35 interactions, where one evacuee assisted another to traverse the three steps from the train to the tunnel. Furthermore, guidance of a fellow participant was registered 31 times, and there were 16 cases where participants offered help to a fellow participant. In only three cases it was observed that a participant assisted a fellow participant to find the exit of the train. The number of instances of assistive behavior shows that people are prepared and willing to assist fellow participants and thereby possibly put themselves at risk. The identified interactions are indicators of a social responsibility among the participants. On the contrary these interactions will affect the evacuation flow and time because people who normally walk faster might adjust their walking speed to the slower evacuee. It is therefore important to be aware of this behavior, while calculating total evacuation times to validate a buildings safety level. Furthermore, the noise level in a building and from the alarm system should be considered in the design in order to enable communication. Even though the exercises were conducted in a controlled environment the observed assistive and altruistic behavior is considered common. Similar behavior is sound in other evacuation studies and is considered a common behavior during real fire emergency evacuations [PII-13 - PII-14].

Building types

The last part of the interview study contained questions regarding the respondents' use of different building types. In the first questions the respondent was asked to identify four different building types, which they visited. The identified building types were beyond the respondent's home, which was excluded from the study. The building types identified by the respondents are displayed in Figure 1. All respondents identified shopping facilities as a building type they visit. In the current study shopping facilities was defined as shopping centers and supermarkets. Seven out of nine respondents mentioned transport terminals (e.g. stations) and sport facilities as a building type they visit. Moreover five of the respondents visited restaurants or cafés. The building types mentioned less frequently was educational, assembly, and office buildings as well as hospitals and concert/theatre venues. The results indicate that the respondents visit a wide range of different building types. Some of the buildings are obvious, but nevertheless it is important to consider the characteristics of building occupants in all types of buildings.

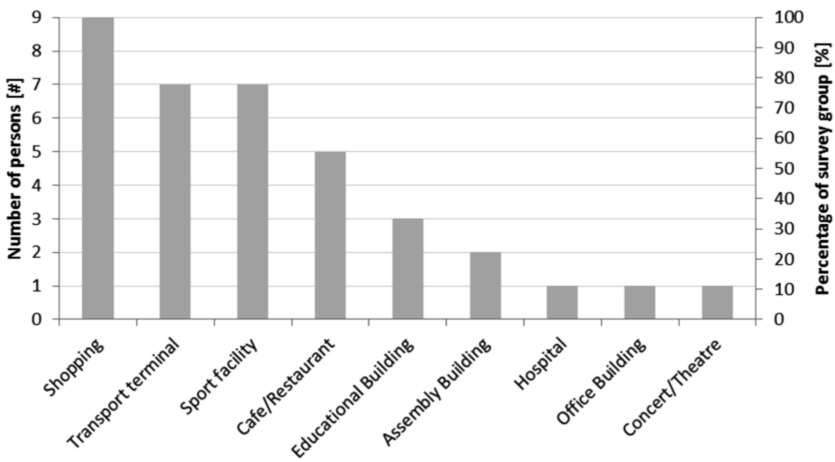

Figure 4.1: Number of persons that has identified varies building types.

The respondents did not identify the same four types of building in the first question and therefore the authors had created a list (the author list) with building types prior the interview. In the following questions the four building types identified by the respondent was supplemented with buildings from the author list to ensure that all respondents answered the rest of the questions based on the same list of building types.

The frequency of visits was examined for the identified building types as well as the building types from the author list. The frequency was examined based on daily, weekly, monthly or annual basis visits, and the results are collected in Table 4. The results show that at least four respondents visited the following buildings on a daily basis; shopping facilities, one-family dwellings, and apartment buildings. On a weekly basis the only building that was visited by four respondents was sport facilities. Monthly four and five respondents visited apartment buildings and cafe/restaurants, respectively. Annually four respondents were visiting concert/theatre venues. The remaining building types (educational, office and assembly buildings, transport terminal, and hospitals) were visited less frequently and only by one to three respondents. The interview did not contain any questions about why a building type was not visited. Nor did it contain question regarding the respondent's employment status. Hence, the questions asked do not enable to determine the reason, why some locations were less visited. However, the results revealed that nearly all building types were visited to some extent by the respondents.

Even though this interview study only includes a small sample size it reveals that the characteristics of occupants are broader than the characteristics of able-bodied adults. The knowledge about characteristics of building occupants plays a key role when accessibility and safety of a building are considered. Furthermore, it is essential knowledge for the fire safety design. The variety of building types identified shows that almost every kind of building is used by people that are considered vulnerable in case of an emergency, according to Figure 1. Consequently, designers and engineers need to consider the vulnerable part of the population, while designing and establishing buildings to ensure a sufficient safety level for this group of people. The frequencies of visits are likewise important as visits on a daily and weekly basis indicate that vulnerable groups of people are frequently present in the building. The buildings identified and the frequency can create a base for engineers and designers to estimate whether the safety system in a certain building should be designed to meet the requirements, the vulnerable segment of our population might have.

Building elements and interior design solutions might generate difficulties for vulnerable people as this might influence the evacuation capability. It is therefore important to consider possibly difficulties during the design phase of a building. The interview study likewise examined the respondents' experienced difficulties to use or pass different building elements. The building elements that were identified as problematic by the responders were; elevators, stairs, escalators, doors, lightning conditions. Problems with elevators were identified by respondents with mobility impairments, where the main problem occurred if an elevator was out of operation. However, elevators could constitute a problem for a person e.g. sitting in a wheelchair who also have a reduced function in arm and hands. Regarding the visually impaired group a problem in elevators is accessible information to determine what floor to go to.

Stairs constituted difficulties for the mobility and visually impaired respondents. The difficulties were distance between handrails, and finding the edge of the treads. Likewise escalators were identified by the mobility impaired respondents to give problems. The problems were to find the edge and the speed of the escalator when getting on and off. These results show that elements to traverse from one floor to another e.g. by use of elevators, stairs etc. might cause problems for the respondents. Additionally, these building elements are often a part of the egress path and the experienced difficulties might result in reduced walking speeds, and thereby an increasing the time it takes to reach a safe place. Similarly, the detected difficulties might influence the total evacuation flow and thereby other evacuees.

Lightning conditions were another parameter that was recognized as problematic for some of the respondents. If the egress path is not sufficiently lit it might be difficult to identify the route to the safe place or find the edge of the stair tread or the door handle on the door. Hence lightning conditions are essential for all evacuees during an emergency because a poorly illuminated egress path will affect the total evacuation time [PII-15]. Poor illumination can be caused by varies factors during an emergency e.g. smoke in the egress path, electric circuit or simply a broken light bulb.

Lastly, some of the respondents answered that they experienced difficulties to travel and navigate in buildings with a high person load. Correspondingly, the number of people might influence the walking capabilities as the surrounded space might be reduced, and thereby affect the ability to evacuate.

Limitations

The results from this study are restricted by the size of the test group as the interview survey only examined a relatively small sample (nine persons). Even though 24 persons with limitations participated in the evacuation experiment only nine of them agreed to take part in the interview study. It was voluntary to participate and the authors could not force anyone to take part. Since the evacuation exercise were held in a controlled environment there might be a lack of realism in the exercises. However, data needs to be collected to constitute the basis for evacuation modelling. Regarding the behavior people might have established some kind of personal relationships during the day since they took part in more than one exercise. These relationships might have affected the behavioral results obtained through the exercises. Therefore the authors emphasize that the obtained results only indicate trends and cannot be generalized. However, precautions should be made on the fire safety design and egressibility to ensure that everyone is equally safe in buildings that are accessible to everybody.

Table 4.4: The frequency of visits for the identified building types and the buildings given in the supplement.

		Shopping	One-family dwelling	Apartment Building	Sport Facilities	Educational Building*	Transport Terminal	Office Building*	Cafe Restaurant	Concert Theatre**	Hospital*	Assembly Building*
daily	Elderly	1	2	1	1	-	-	-	-	-	-	-
	Hearing	1	2	1	1	2	-	-	-	-	-	-
	Mobility	2	2	-	1	1	-	-	-	-	-	-
	Vision	2	-	2	-	-	2	1	-	-	-	-
	Total	6	6	4	3	3	2	1	-	-	-	-
weekly	Elderly	2	1	-	-	-	-	-	1	-	-	-
	Hearing	1	-	-	1	-	1	-	1	-	-	-
	Mobility	-	-	-	1	-	1	-	-	-	1	-
	Vision	-	1	-	2	-	-	-	-	-	-	-
	Total	3	2	-	4	-	2	-	2	-	1	-
monthly	Elderly	-	-	1	2	-	1	-	1	1	-	-
	Hearing	-	-	1	-	-	1	-	1	1	-	-
	Mobility	-	-	2	-	-	1	-	1	1	-	-
	Vision	-	1	-	-	-	-	-	2	-	-	-
	Total	-	1	4	2	-	3	-	5	3	-	-
annually	Elderly	-	-	1	-	-	2	-	1	-	-	1
	Hearing	-	-	-	-	-	-	-	-	1	-	1
	Mobility	-	-	-	-	-	-	-	1	1	-	-
	Vision	-	-	-	-	-	-	-	-	2	-	-
	Total	-	-	1	-	-	2	-	2	4	-	2

* Building type not a part of the author list.

** Total number does not add up to nine, as two participants answered "never".

Conclusion

In the current work accessibility and egressibility of buildings are studied. Building types, visited by members of the vulnerable part of the population are identified. The group in focus comprises people with physical and cognitive disabilities as well as individual's aged younger than 5 years or older than 64 years. All members of the group were participants of an evacuation exercise carried out from a train in a test tunnel. In an interview study the participant's activities away from home were surveyed as well as their experience of the evacuation experiment.

The respondents' experiences regarding perception of the alarm and movement during the evacuation exercise were assessed as a part of the interview survey. Difficulties with perception of the alarm were dependent on the type of impairment. The hearing impaired respondents experienced the largest difficulties, which resulted from the verbal alarm used in the experiment. The elderly people did not experience any difficulties with the alarm. Movement towards safety was also investigated, and the elderly people and the hearing impaired did not report any difficulties in moving to safety outside the tunnel. On the contrary the stairs were difficult to traverse for both the mobility and visually impaired respondents.

The interactions registered during the evacuation exercises show that it was common to lend a helping hand to a fellow participant. An altruistic behavior was a very common behavior among the participants.

The last part of the interview study that assessed the use of different building types showed that elderly people and people with impairments visit all kind of buildings. This is important knowledge for designer and engineers to ensure that the safety level in a particular building is sufficient for all occupants whether or not they have impairments or limitations. The building types identified by the majority of the respondents were; shopping facilities, transport terminals, sport facilities and café/restaurants. The frequency of the visits varies among the respondents and the building types. This indicates that only a single category of occupancy for the vulnerable group is not representative because this group is present in almost all kind of buildings.

Difficulties experienced with different building elements were also examined and the respondents recognized building elements to traverse from one floor to another to give problems. The specific building elements were stairs, elevators and escalators. In addition lightning conditions were identified to generate problems for some of the respondents. Lightning conditions can affect the evacuation flow of both people with impairments, but also able-bodied people. Poor lightning condition might result in a decreasing ability to orientate in the egress path.

The experiences reported by the respondents identify where people with different types of impairments experience problems. These problems could then be addressed and solved during the design phase of a building to ensure an equal safety level for everybody.

Acknowledgement

Thanks to Silvia Arias for assistance in processing data, the Interreg IV A Öresund Kategat Skagerak program (European Union) for funding the work through the project KESØ and Trygfonden.

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Chapter 5

Validation of Evacuation model using real data - What is the influence of the composition of the population?

Thesis Paper	III
Title:	**Validation of evacuation mode using real data**
	What is the influence of the composition of the population?
Author:	J.G. Sørensen and A.S. Dederichs
Journal:	Conference Proceedings Interflam 2013, Fire Science and Engineering Conference
Status:	Published
Keyword:	modelling, evacuation, occupant characteristics, vulnerable people, train, tunnel

Abstract

The influence of the composition and heterogeneity of the population of the evacuation times in real fire drills and the prediction of the total egress times using STEPS are investigated in the current work. The evacuated building was a train in a tunnel in KorsÃ¸r, Denmark. The experimental study was carried out in 2012 and engaged 100 participants in the age from 6 to 75 years. Besides able-bodied people, the participating population consisted of subpopulations covering hearing, visual, mobility and cognitive impairments. The mean free walking speed was detected for all subpopulations as a mean of the individual speed taken prior the experiments. They served as input to the software STEPS. The total egress time was measured and calculated with the numerical tool. Different setups with varying compositions, blending in and out different subgroups of the population, were run. It was found that accounting for heterogeneity of the population doubled the total evacuation time compared to neglecting it. The predictions of STEPS could be improved by adjusting the speed distribution. The human behavior occurring in the experiment affected the egress times. The simulations did not account for these phenomena.

Introduction

During the past decades the demand for complex buildings and structures has increased. As a consequence engineers have experienced difficulties in fulfilling prescriptive requirements for the fire safety. Performance based fire safety codes have therefore been implemented in many countries around the world as a supplement to the existing prescriptive codes. The implementation of performance based codes enable the fire safety design of complex buildings. The use of performance based codes allows engineers to use fire safety engineering tools such as computer models, to proof that the safety level in the current building is sufficient. On one hand CFD codes are used to compute the time until untenable conditions occur, the so-called available safe egress time (ASET), whereas evacuation models are used to predict the time required for evacuation (RSET). In this paper the focus is on the evacuation models and the need for valid input data (e.g. walking speeds and delay times) for the prediction of realistic evacuation times. The majority of studies on walking speeds and delay times from literature deal with the evacuation behaviour of homogeneous groups, often able-bodied adults, and applies normative standards for the choice of population[PIII-1]. However, a homogeneous group of able-bodied adults are rarely representative for the population in a building. 15 % of the world's population is disabled in some concern and additional 10% are elderly people[PIII-2]. These groups need to be safe in buildings in the same manner as able-bodied adults.

Literature background
Literature contains a series of models describing the evacuation process[PIII-3].

Some of the models are not validated, others apply different methods ranging from: results from fire drills, people movement experiments, literature on past evacuation experiments, code requirements, validation against other models or third party validation. However, not only the method of validation differs, also the parameters focused on, while validating differs. Besides parameters related to the respective building, such as nature or function of enclosure and the fire, E.R. Galea lists "nature of the population", such as "age/gender distribution" as well as, "physical attribute distribution" as parameters, which should be controlled, when an evacuation model was validated[PIII-4]. Empirical investigations have shown that age, gender, time of day among other parameters affect the average walking speeds[PIII-5], as well as interpersonal distances and densities[PIII-6].

19 out of 26 egress models reviewed by Kuligowski et al. allow a description of the evacuation of disabled people[PIII-3]. The question rises if and how the models have been validated against these populations, where data is rare. How do these models handle the heterogeneity of a real population and the inclusion of disabled people in the building environment? The effect of heterogeneity on self organized pedestrian flows has been investigated by Campanella et al.[PIII-7]. Here the heterogeneity was accounted for by varying the diameter of pedestrians, reaction times and walking speeds. It could be seen, that an increasing heterogeneity in the population affects average speeds, densities and more likely lead to break down of the flow. It was concluded from the Campanella study that the heterogeneity of models has a large impact on the flow and needs to be considered.

Aim of the project
In the current study the evacuation modelling software STEPS (Simulation of Transient Evacuation and Pedestrian movementS) is assessed with respect to "nature of the population". The model has been validated against code requirements, people movement experiments as well as literature on past evacuation experiments[PIII-3]. STEPS was used to simulate scenarios implying homogeneous and heterogeneous flows. Evacuation times obtained during real evacuation exercises of four different scenarios are compared to times determined with a computer simulation of the exercises.

The purpose of this project was to examine data from evacuation exercises performed from a train in a tunnel in the city of Korsør, Denmark, to determine egress paths and the walking speeds for each occupant who participated. The video footage from the evacuation experiment were analysed to determine walking speeds. Furthermore, the total evacuation times of the various evacuation scenarios are examined by using the simulation tool in which the previously discovered walking speeds serves as input to the model.

This paper contains a description of the method used in performing the evacuation experiments. In addition the evacuation model build up in STEPS is explained. The section on results comprises total evacuation times for the real exercises compared with the simulations and a discussion of the findings. In the conclusion the main highlights of the current work is presented and future work is suggested.

Method

In the present section two methods are described. At first the method applied for determining the average walking speeds and total egress times for each subpopulation represented in the evacuation experiment. Furthermore, it is described how the associated evacuation calculations are performed using the program STEPS 5.0. The average walking speeds found for each subpopulation are added into STEPS 5.0 in order to perform simulations of the experiment.

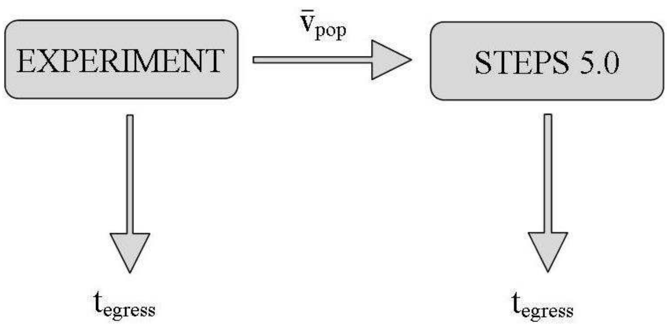

Figure 5.1: Connection between experiments and simulations

The connection between the experiment and the simulations performed with STEPS is illustrated in figure 5.1. The mean velocities for every subpopulation, $\bar{v}_{pop}$, obtained for the unimpeded walking in the experiment serves as input to the STEPS model. Two different times for egress, t_{egress}, are achieved and are compared in a later section.

Experimental Setup
The evacuation experiments are performed from an IC3 train in a tunnel, both in full scale. The test tunnel corresponds to the rail tunnel, connecting Zealand and Funen in Denmark, the Great Belt link. The real tunnel has two parallel pipes that are connected with 31 transversal tunnels. The transversal tunnels are used for installations and as a part of the egress path. In the current experiments the tunnel section is 60 meter long and is provided with two transversal tunnels with an internal distance of 40 meters. The capacity of the train is 23 seated passengers and 13 standing passengers in the carriage, and additional 10

standing passengers in the corridor between the carriage and exit doors. The train is placed in one end of the tunnel and the evacuees are told to use the nearest transversal tunnel to reach the safe place. People in the experiments are considered safe when exiting the transversal tunnel. In the real tunnel this corresponds to the opposite tunnel pipe. The total egress times are measured as the time where people leave the transversal tunnel.

During the experiments four different compositions of the test group are applied. Each of the four scenarios was replicated five times resulting in a total of 20 evacuation exercises. The reference scenario consists of only able-bodied adults whereas the other three setups in- and exclude mobility impaired participants, visually impaired participants and children, respectively. The composition of the test groups was matched as close as possible to the demographic profile of Denmark. Table 5.1 gives an overview of the number of each type of participants in the four setups.

Table 5.1: Distribution of people in the different scenarios.

	Scenario			
Characteristics	1: Reference	2: -Mobility	3: -Visual	4: -Children
Able-bodied	46	23	23	28
Children	-	8	8	-
Cognitive	-	2	2	2
Elderly	-	8	8	8
Hearing	-	3	2	3
Visual	-	2	-	2
Mobility	-	-	3	3

The experiments were recorded with temporarily installed video cameras. The raw video footage was analysed after the exercises using Adobe Premiere Pro. Total evacuation times for each of the scenarios were determined. In addition, the free walking speed on horizontal planes for each participant, hence, for each subpopulation, was found, and is presented in a later section. The data on the unimpeded walking speeds serves as input to the evacuation model in the evacuation modelling software STEPS.

Simulation in STEPS
STEPS is a simulation program based on a discrete cellular automata model, with a basic assumption on only one person in each grid cell. The size of the grid was determined on the basis of the projected area an adult occupy of the floor area. From previous studies it is given that the projected area of an adult is 0.46 meters in summer dress and 1.1 meters if baggage is included[PIII-8]. In the current simulations a grid size of 0.5 meters is chosen because the partici-

pants are wearing more cloth than just summer dress and are told to leave their baggage behind. Hence, the space between people was considered. Due to the chosen grid size the maximum person density in the simulations are 4 $pers/m^2$, independent of the actual size of the persons.

The grid used in the model and the numbering of seats are displayed in figure 5.2. The size of the grid induced minor changes in the train dimensions to fit the grid of 0.5 meters. However, it was assumed that small changes will not influence the result. The slightly changed design of the train and the chosen grid size allows a maximum capacity of 52 persons. However, it was chosen to follow the experimental setup and occupy the train with 46 passengers. The positions indicated in figure 5.2 shows the initial start position for each participant.

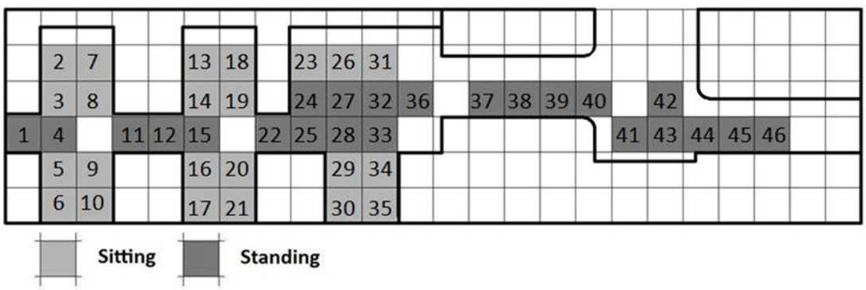

Figure 5.2: Seat numbering in the train and display of the grid system.

The stair between the train and the tunnel was modeled as an independent plane. The grid of the stair planes was 0.625 meters resulting in a width of the stair of 1.25 meters, which corresponds to the actual width of the component.

STEPS applies default values for walking speeds. The software offers a Fruin distribution for the population. In the current study the position of the participants in the simulation fully corresponds to the evacuation experiments performed in the tunnel and was defined for each position in each setup. To investigate the differences between the model and the evacuation experiments the mean free walking speed for each subpopulation was used as input values to the model. The results on the mean free walking speed horizontally, input for the model, are presented in a later section.

It is known from previous studies that the walking speed is affected by the person density[PIII-8 - PIII-10]. STEPS gives two pre-defined options for the relation between the walking speed and the person density; one by the use of the speed/density curve given in the SFPE handbook[PIII-11], and one with the use of the interpersonal distance curve developed by Dr. Peter Thompson[PIII-12] for the simulation software Simulex. The evacuation exercises are modelled using both these two methods to investigate the differences. Each simulation of the four scenarios was run 15 times.

Analysis of free walking speeds
The free walking speed for each participant was determined based on the video footage. Before each experiment the participants were asked to walk individually through the transversal tunnel as they would normally walk. The walking speed was determined over a distance of 6.62 meters. Each participant was only measured the first time they participate in the exercises.

Results and Discussion

The resulting mean free walking speed measured in the evacuation experiments, input to the simulations, as well as the individual total egress time will be presented in the present section. In addition the results from the simulations are presented and compared with the experiments.

Mean free walking speed
The mean free walking speed for each of the subpopulations is showed in table 5.2. In the table the values given in various guidelines and found in literature are likewise displayed. Generally, the walking speeds measured in the experiments are higher than the values suggest by guidelines and found in literature. It is also seen that children and hearing impaired participants walks faster than able-bodied adults. The different populations are not represented with the same number of test persons. Furthermore, they have a varying degree of disability.

Table 5.2: Distribution of people in the different scenarios.

Person type	mean $[m/s]$	min $[m/s]$	max $[m/s]$	Guidelines	Literature
Able-bodied (n=58)	1.69	1.59	1.80	1.19-1.3	
Elderly (n=12)	1.43	1.20	1.66		0.91[III]
Children (n=16)	1.89	1.70	2.08		0.6-0.84[I]
Hearing impaired (n=3)	1.81	1.28	2.33		
Cognitive impaired (n=4)	1.55	0.35	2.76		
Visually impaired (n=3)	1.53	0.89	2.16		0.96[IV]
Reduced mobility (n=3)	1.02	0.89	1.15		0.8[II]

[I] Larusdottir & Dederichs, 2013, [PIII-13]
[II] Boyce et al., 1999, [PIII-3]
[III] Knoblauch et al., 1996, [PIII-14]
[IV] Sørensen & Dederichs, 2013, [PIII-15]

Total evacuation time

The total evacuation times found in the experiment and the simulations are given in table 5.3. Here it is seen that the evacuation time for the scenarios with a mixed population is twice the time as for the reference scenario with only able-bodied adults. Table 5.3 shows that the total evacuation times are affected by the method used to simulate the relation between the walking speed and person density. If the speed/distance curve, developed by Dr P. Thompson[PIII-12], is used in the simulations it gives evacuation times around 50 second with a spread of 1.3 seconds. This small spread means that there is hardly no difference between the scenarios with a mixed population and a homogeneous population even though the experiments show that there is a factor two in difference on the total evacuation time. On the contrary, if the speed/density curve from the SFPE Handbook is used the total evacuation times lies in the range from 111 second for the reference scenario up to 132 second for the scenario without visually impaired participants. Comparing the times in the speed/density simulations with the experiments shows that for the reference scenario the predicted total time is doubled. For the scenarios with mixed populations the time obtained in the simulations is in the same range as the total times from the experiments.

Table 5.3: Total evacuation times for the experiments and the two types of simulation.

Setup	Experiment [s]	Speed/Distance [s]	Speed/Density [s]
Reference	56	50	111
Without mobility	110	51	117
Without visually impaired	127	52	132
Without children	108	53	123

The results for the total evacuation times predicted by the simulations do not give a precise answer on what relation between the walking speed and person density should be used. The speed/distance curves give a time, which coincides better with the experiments for the reference group of able-bodied adults than the speed/density distribution. The speed/density curve coincides better with respect to total evacuation times when comparing with the scenarios with mixed test groups.

Individual egress times - experiment and simulations

In the following section a detailed quantitative comparison between the simulations and the experiments will be presented based on the individual egress times.

Figure 5.3 shows the prediction of the total egress time for the reference scenario compared to real data from the experiment. The number of data points in the experiments does not coincide with the number of data points in the simulation. This is due to limitations given by the recruitment process. From the figure it is seen that the slope for the speed/distance curve corresponds to the one achieved in the experiments. However, the first person has evacuated after 8 seconds in the simulation, whereas the first person is out after 12 seconds in the experiments. The exiting flow for the simulation is therefore shifted to the left. The two curves for the experiments and the simulation using the speed/distance relation shows comparable linear trends. The progression of the exiting path for the simulation using the speed/density relation is however, different. The first approximately 15 people evacuate similarly to the experiments and the simulation using the speed/distance relation. After 15 people have evacuated the curve breaks and continues with a slope less steep than for the two other results. This is general for all four scenarios and will be explained later in this section.

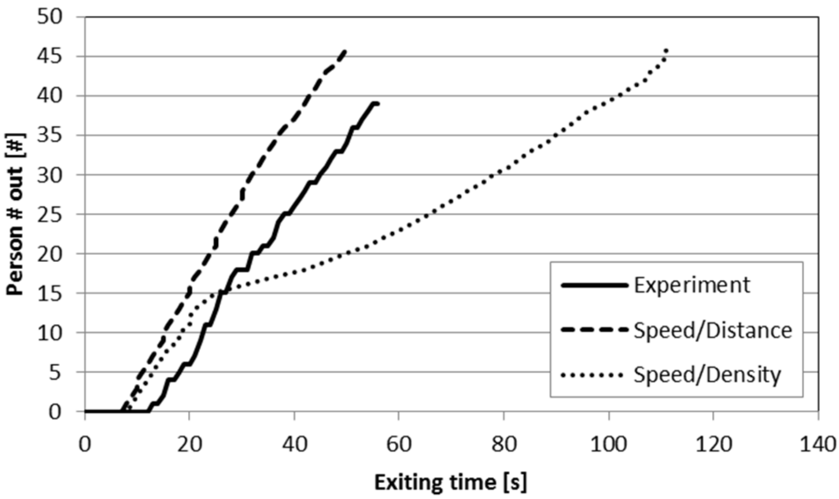

Figure 5.3: Exiting flow for the reference scenario obtained in the experiments (continued black line) and predicted by the simulations.

The egress of a population with only able-bodied adults is best described using the speed/distance relation. However, the simulations predict a lower evacuation time and a safety margin should be applied to the predicted results from the simulations.

Figure 5.4 displays the exiting time for the scenario where people with reduced mobility are left out. The experimental data shows horizontal plateaus, where nobody is evacuating. These are moments, where people are helping each other, instead of overtaking slower walking participants and maintaining a constant flow. The simulations applying the speed/distance relation predict total evacuation times of around 50 seconds. The simulations applying the speed/density relation have a slope corresponding to the results from simulations applying speed/distance curve until approximately 15 people have evacuated. After that point the curve breaks and continues with a slope less steep as will be explained later in this section. Both simulations (speed/density and speed/distance) predict exiting flows that can be considered constant. In both cases slower walking participants are not shown to hinder the flow. The evacuation time that gets closest to the total time obtained in the experiments is when the speed/density relation is applied. From the result it is not possible to suggest the most appropriate way of simulating the exiting path for this scenario. However, if the total evacuation times are isolated the predicted value for the simulation using the speed/density relation is the one that gets closest to the time from the experiment. In addition this time is a conservative choice.

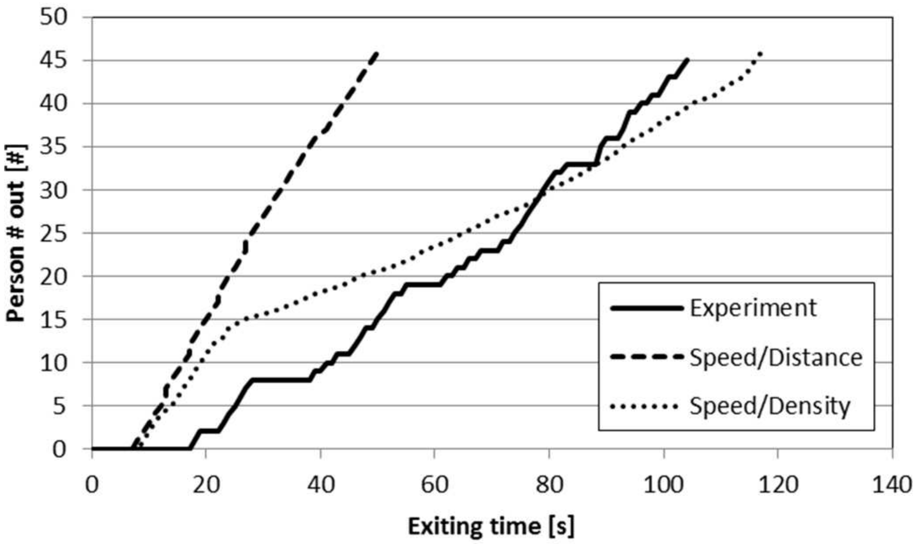

Figure 5.4: Exiting flows for the scenario where mobility impaired participant are not represented. Experiment is the black line, and the simulations are the dotted lines.

The results for the scenario, where people with visual impairments are excluded from the egressing populations are displayed in figure 5.5. The exiting flow for the two simulations are following the trend of the two previously described scenarios. The flow for the simulation using the speed/distance relation has a steep constant slope with a total evacuation time on 52 seconds. The exiting flow for the simulation using the speed/density relation is similar to the one for the speed/distance relation but breaks after 13 people. After the break the curve continues with a less steep progression and ends with a total evacuation time of 132 seconds. The exiting flow for the experiment can be divided into two parts with similar slopes. It is seen from the figure that after 58 seconds until 81 second no people evacuate. This is explained by the formation of a queue in the egress path. The video footage shows that one of the mobility impaired participants is subject for the queuing. Faster walking participants do not overtake him and therefore nobody exit the tunnel in the particular time span. It is apparent from figure 5.5, that none of the simulations are able to predict the behaviour observed in the experiments.

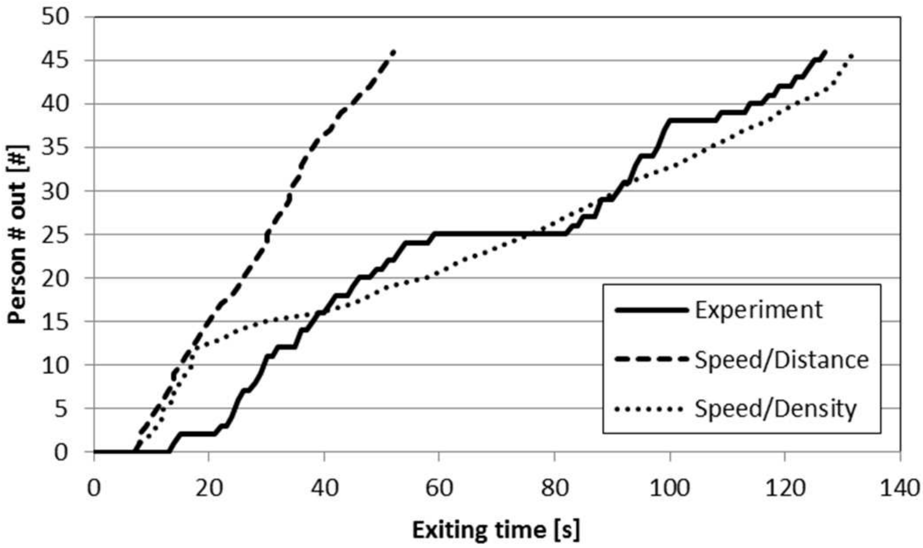

Figure 5.5: Exiting flows for the scenario where visually impaired participant are not represented. Experiment is the black line, and the simulations are the dotted lines.

In the last scenario the subpopulation "Children" is excluded. The results are presented in figure 5.6. The two simulations are similar until approximately 15 people have evacuated. After this point the curve for the speed/distance relation continues, with unchanged slope until the evacuation is completed after 53 seconds. The curve for the speed/density relation breaks and continues with a less steep slope until the evacuation is completed after 123 seconds. The result from the experiments shows that the exiting flow is split into several parts. The exiting flow cannot be considered constant during the evacuation as predicted by the two simulations. Also in this scenario there is a time sequence in the middle where nobody has reached the place of safety. The exiting flow for the simulation using the speed/density relation is the one, which is closest to simulate the precise exiting flow during the experiment.

In all four scenarios it is observed that the curve for the simulation using the speed/density relation breaks after 15 persons have evacuated. Assessing the

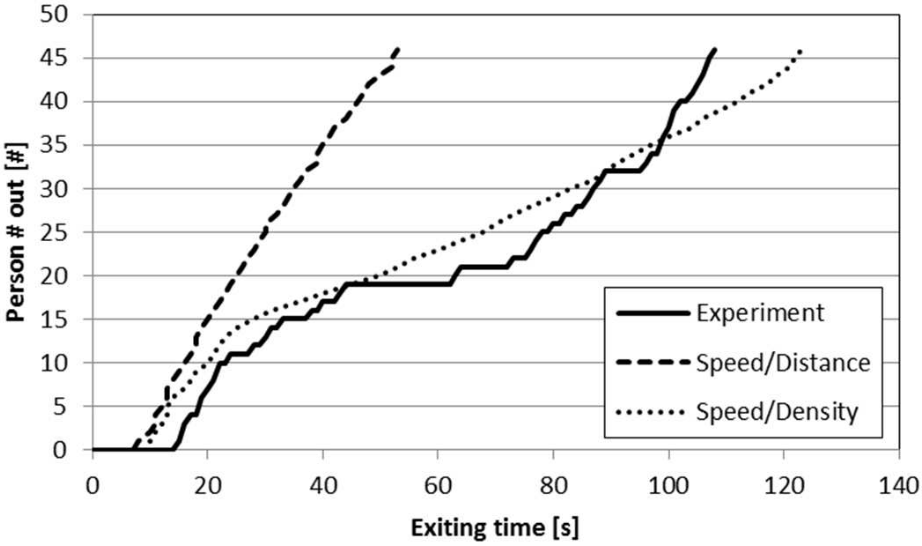

Figure 5.6: Exiting flows for the scenario where chldren are not represented. Experiment is the black line, and the simulations are the dotted lines.

simulations shows that the door between the carriage and the corridor creates a bottleneck that controls the flow for the people situated in the carriage from the beginning of the exercise. The less steep curve is therefore explained by the flow capacity of the bottleneck. Another parameter that affects the flow through the bottleneck is the density. Using the speed/density relation applies a maximum person density of 3.8 $pers/m^2$, which conflicts with the grid size chosen, as the grid allows for a maximum density of 4 $pers/m^2$.

The results presented in the previous section shows that none of the options for the walking speed density relation giving in STEPS is able to model what happens during the evacuation experiment, even though the walking speeds is adjusted to match the values measured in the experiments. It is seen that the behaviour observed for the scenarios with a heterogeneous population cannot be modelled in the program. None of the simulations are able to predict a non-constant evacuation flow and take into account that people will assist each other, as observed during the evacuation drills with heterogeneous populations. Furthermore, the inclusion of vulnerable population groups is not affecting the simulation using the speed/distance curve. This is however clearly seen in the experiments.

This study shows that the parameters in STEPS should be handled very carefully because the predicted total evacuation times differ from each other. In the presented case the speed/distance option gave the best results for a homogeneous group of able-bodied adults. Contrary, the speed/density option was able to get closest to the exiting flow for the three scenarios with a mixed test population.

Comparing the evacuation flow for the mixed and homogeneous test groups shows that able-bodied adults are able to maintain a constant flow. Contrary to this plateaus are observed for all three scenarios with mixed populations. The plateaus illustrates that no people exit the tunnel. The reason for that is that people are assisting each other and thereby reduce their walking speed. Furthermore, it is seen that able-bodied people behave differently dependent on the composition of the population, as participants from the reference scenarios, only comprising able-bodied adults, also participate in the exercises with mixed populations.

In both the experiment and the simulations the first part of the curves displays how the lobby is emptied. The exiting flow for this part is constant and similar for all four scenarios. The remaining flow is partly controlled by the bottleneck between the carriage and the lobby corridor and the density in the carriage. Furthermore the evacuation ability of the subpopulations affects the flow for the people situated in the carriage.

Limitations
The participants in the experiments are not only used for one exercise or replication, due to limited number of test persons. It is therefore reasonable that the participants have established some kind of a personal relationship during the experiments. This personal relationship might have influenced the results because people might have been more willing to assist each other. The optimum setup of the experiments would be only to use each participant once.

It is seen from the results that the evacuation time is increased using the speed/-density for all four scenarios even though the composition of the test population is varied. This might be explained by the chosen grid, and not the heterogeneity of the population. Hence, the simulations performed in this study do not indicate that the software tool is capable of modelling the human behaviour.

In a real situation the evacuation flow from the transversal tunnel will be affected by the evacuees' ability to distribute in the opposite tunnel. If the evacuees hesitate to distribute, congestion might occur in the transversal tunnel and thereby reduce the evacuation flow. In the experiments there were no opposite tunnel pipe and people were considered safe outside the tunnel and no congestion in the transversal tunnel were observed.

Conclusion

The current experimental and numerical study deals with the evacuation of homogeneous and heterogeneous populations from a train in a tunnel. The heterogeneous population consists of the following subpopulations: able-bodied people, children and elderly people, people with mobility, visual and hearing as well as cognitive impairments. Walking speeds for the different subpopulations, are measured in the experiments and used in the evacuation software STEPS, a numerical tool, that allows the inclusion of people with impairments. The focus of the work was to study the effect of heterogeneity on the evacuation times. This was done running four different compositions of the population, starting with the reference scenario consisting of only able-bodied adults and leaving out different subpopulations from a heterogeneous mixture compared with real data of the same scenario.

The first findings are on the average walking speeds. Of the average speed, the highest value was seen for children. This is due to the fact that the participating children are more eager than adults and therefore almost are running through the corridor where the walking speeds are measured. The second highest walking speed was seen for people with impaired hearing. However, only three test subjects participated in this population category, so there are few measurements and therefore a large uncertainty in the calculated average speed. Elderly and people with low mobility have a lower walking speed than able-bodied, as expected. With the exception of those with low mobility, the walking speeds of all population groups are greater than the walking speed, which is usually used for evacuation analysis. The reason is that normally a more conservative estimate of the means of escape for a given building is used.

The second finding is that the total evacuation times obtained in the different exercises depend on the composition of the population. The total egress time for the drills involving a test population only consisting of able-bodied adults is half the total evacuation time compared to the drills involving heterogeneous populations. This is noteworthy as the common used data for evacuation models often bases on able-bodied adults, and it can be discussed whether this is representative for a real population. A comparison between the remaining three exercises shows that the average total evacuation times are within the same time interval.

The study shows that there is a difference in the total evacuation time dependent on the composition of the studied population. In addition, it shows that a test population closely corresponding to the demographic profile of Denmark evacuates the train and tunnel at a time, which is twice the one for a heterogeneous population. Finally, the evacuation software STEPS was used to predict the total egress times of the scenarios. This was done applying the free walking speeds from the first part of the experiments as input. Depending on the setup the total egress times match better the able-bodied scenario than the heterogeneous blend. The effect of the input velocities is smaller than the effect of the chosen speed distributions. The effect of human behaviour, such as helping each other and choosing not to overtake affect the flow. These phenomena cannot be accounted for in the model.

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Chapter 6

Evacuation Characteristics of visually impaired people - a qualitative and quantitative study

Thesis Paper	IV
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	a qualitative and quantitative study
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Abstract

Evacuation characteristics for blind and visually impaired people are presented in the current study. 40 participants in the age from 10 to 69 years with impairments for all of the four Danish categories (A-D) took part in the study. The mean free walking speed descending stairs for category C and D were found to be comparable with values found in Danish and Swedish guidelines. The walking speed of people with visual impairments was not affected by an increasing density on stairs to the same extent as the walking speed of able-bodied adults. It was found that people with visual impairments were able to uphold a higher walking speed descending stairs than able-bodied adults for increasing person density. The initial walking speed on horizontal planes is lower than the value suggested in literature. The horizontal mean free walking speed depends on the degree of vision loss. The design of the building environment is important for the ability to orientation for people with reduced sight. Walls and handrails are important for the self-orientate possibilities for people with visual impairments. The findings in the current study are indicative trends for evacuation characteristics of blind and visually impaired people.

Introduction/Background

An increased complexity of buildings erected in the past decades has implied an increased demand for flexible regulations in building design, including the fire safety design. Traditional prescriptive codes generally prohibit this type of design. Hence, performance-based codes have been developed since the middle of the 20th century and implemented worldwide over the past twenty years [PIV-1], [PIV-2], allowing engineers to verify the safety within a building using fire safety engineering tools. Performance based codes give the possibility to design a building in a more innovative and sustainable way, without being restricted by requirements on e.g. distance to nearest exit as long as the safety level is documented by calculations or other means.

Early studies within evacuation and pedestrian flow dynamics have primarily focused on characteristics of able-bodied people [PIV-3 - PIV-5], and models for walking speeds horizontally and on stairs as well as models for evacuation flows were developed. These models create the foundation for many of today's national and international guidelines used while designing the fire safety of a building [PIV-6 - PIV-8]. However, data on vulnerable people are limited and consequently difficult to rely on when developing and validating models. These groups of vulnerable people are not accounted for in most models and it is therefore questionable if this part of the population is equally safe in buildings comparing with able-bodied adults [PIV-9]. Furthermore, recent investigations show that the vulnerable part of the populations is more likely to suffer during emergencies [PIV-10], [PIV-11]. Little information on evacuation characteristics of people with impairments is found in the literature specifically on blind and visually impaired people [PIV-12 - PIV-14]. However, an increasing focus on the safety of this group is established among researchers and legislators [PIV-15], [PIV-16]. Data used to develop models is therefore needed for this group to achieve representative predictions of evacuation times. It is not possible to neglect the vulnerable groups (i.e. children, elderly people and people with disabilities) in society as they represent nearly 40% of the world's population [PIV-17]. The blind and visually impaired people constitute 4% of the total world population [PIV-18]. However, it is known that the majority of people with reduced vision live in developing countries [PIV-18]. In Denmark it is estimated that approximately 1% of the population are blind or visually impaired [PIV-19].

Often computer models are used to simulate evacuations and predict evacuation times for complex buildings. In many of these models the population can be divided into groups' described by different evacuation parameters e.g. walking speed. Unfortunately, input data to the models are inadequate, as the majority of data is based on able-bodied adults and do not describe people with disabilities. Furthermore, not all vulnerable groups of the population are properly described with respect to their evacuation characteristics In addition, the increased focus on civil rights and access for people with impairments has entailed law requirements on accessibility to the building and urban environment [PIV-20 - PIV-22]. It is therefore assumed that the presence of people with impairments in the building environment is increasing. An indicator that confirms this is an increase in employment of people of this particular group of people within Europe [PIV-23], [PIV-24]. However, accessibility to the building environment is not a guarantee for egressbility and the vulnerable people need to be safe in the same manner as able-bodied adults.

Another aspect is the demand for sustainable building design. Social quality is one criterion of many applied for the evaluation of sustainable building design [PIV-25]. This factor requires consideration of all the users of a building in the design ensuring equal opportunities for all occupants. With respect to fire safety this means egressibility and avoidance of a design that disables parts of the population in participating in the evacuation, leaving them to be rescued by the emergency services in a later stage of fire development. To meet these requirements, the evacuation of all parts of the heterogeneous population, consisting of different subpopulations, need to be investigated qualitatively and quantitatively.

The aim of the present study is thus to provide designers and engineers with realistic data and models on evacuation design parameters for blind and visually impaired people, mainly walking speeds horizontally and descending stairs, and give an overview of factors that influences the human behaviour of this group.

In this paper the performed evacuation experiments and details about density measures and ethics are described. Results on walking speeds horizontally and descending stairs are presented and discussed. Likewise, the influence of interactions between participants on the evacuation characteristics is discussed.

Methodology/Experimental setup

The presented work is based on an experimental study of various evacuation parameters for blind and visually impaired people, namely walking speeds horizontally and descending stairs and the social bond and interactions between participants. The experimental period was from February to May 2011. The exercises were carried out in four different buildings in different cities in Denmark. The buildings can be divided into two types of buildings: one with two storeys and one with three storeys. In common for the buildings are that the egress paths consist of corridors and stairs. The experimental setup consisted of three different types of evacuation exercises:

- evacuation of a single person
- evacuation of groups
- unannounced full scale evacuations

The test group consisted of 40 participants with different degrees of vision loss, different gender and ages, specifically 26 males and 14 females aged between 10 years and 69 years.

The test group is divided into four subcategories (A-D) dependent on the degree of vision loss according to the Danish national classification system, [PIV-26]. The Danish national classification is based on the best-corrected visual acuity in the better eye. People with a visual acuity of 0.3 measured in the better eye is considered visually impaired (category A), and people with a visual acuity of 0.1 measured in the better eye is considered legally blind [PIV-27]. The latter group is further divided into three subcategories consisting of social blindness (B, $\leq$0.1 - $>$0.01), practical blindness (C, $\leq$0.01 - $>$0.001) and total blindness (D, $\leq$0.001), [PIV-28]. The size of the test group within each category is given in Table 6.1.

Data recording
The data was collected using temporarily fixed video cameras. The cameras used for recording were of the type X170 Drift Innovation, which is a small action camera. The size of the camera (133x50x33 mm) was important because interference with the surroundings should be limited as the experiments were performed in the participant's natural environment. The cameras were

Table 6.1: Number of test participants in each of the Danish categories

	Category A	Category B	Category C	Category D
Male	2	7	8	9
Female	4	5	1	4
Total	6	12	9	13

installed in two different ways - filming directly from above to measure densities and walking speeds, and turned an angle to observe interactions among participants, see Figure 6.1. The raw video footage was analysed using different computer software.

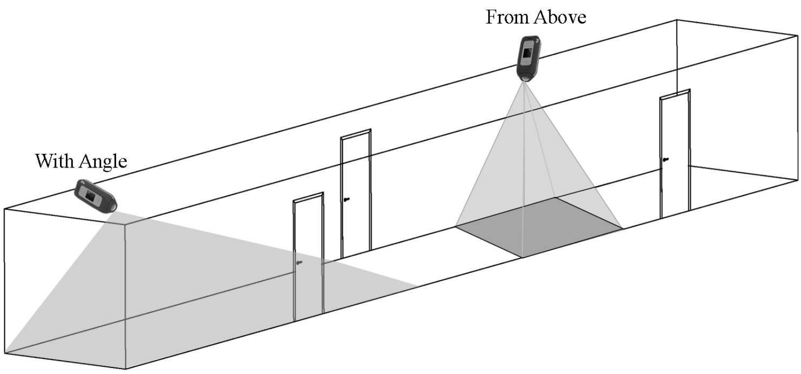

Figure 6.1: Mounting of cameras filming from above and with an angle.

Density Measurement
On horizontal planes the density is measured within a reference area of 2 m^2. The area is determined as 1 meter in front and behind the particular studied person and the width is 1 meter with the particular person centred, more information on the densities can be found in Sørensen & Dederichs [29]. The local density registered by the person is considered using this method. Hence, it is assessed more representative comparing with a global density measured within a larger area. In addition, unrealistically low densities are avoided. The limitation of this method is that densities below 0.5 m^2 cannot occur, because the person load within the area always is at least one person. Furthermore, people walking with a guiding dog accumulate a higher density, because the dog is counted as a person in the current study, as it is assumed that the presence of the dog influences the evacuation flow. Literature within the field provides different ways of measuring density [PIV-30], [PIV-4], [PIV-31]. Applying this method to the current study entails a large number of data points for densities for 0.5 $pers/m^2$ and 1 $pers/m^2$. This is due to people walking alone or only with their guiding dog.

The density measurements on stairs are different from horizontal planes. In the current study two methods for measuring densities on stairs are applied. The methods depend on the design of the stair. If the stair between two floors is a straight single flight stair, the density is measured in two parts, where the stair is split equally, vertically. If it is a two flight stair with an intermediate landing, the density is measured on each stair flight. Using this method error, regarding the distribution of people on the stair, can be minimized. If a stair between two floors contains more than two flights, the density is measured on every flight.

Ethics

The procedure for ethical approval in Denmark is different from other countries [PIV-32], [PIV-33], [PIV-34]. Projects categorised as register research projects, that do not incorporate any biological material do not need an approval by the Danish ethical committee. The current study falls within this category of register research and an approval is therefore not required. However, the research team at the Technical University of Denmark developed specific ethical requirements for the current experiments in an attempt to meet their own demand as well as common practice with respect to ethics in other countries. On that basis participants received written and oral information before the experiments; they signed an informed consent permitting filming and use of the results. In addition participants were guaranteed anonymity and were informed that the exercises were held on a voluntary base. Furthermore, they were not exposed to any extraordinary conditions such as smoke, heat or flames and could withdraw at any time.

Even though approval by an ethical committee is not required, the project is approved by the Danish Data Protection Agency, since health related data can be processed and identified from the video footage. The agency defined requirements on processing and storing data.

Limitations

The experiments are conducted in the participants' natural environments, which have entailed variations in the experimental setup and installation of cameras is restricted by the interior design of the test locations. The variations are unavoidable but are taken into account in the analysis where chequered mats are used to determine specific walking paths.

Unexpected behaviour was observed during the full scale experiments. This has induced a smaller data sample, because not all possible egress paths were covered with cameras. Such incidents are hard to predict and is a part of performing experiments involving human beings.

The size of the test group is not statistically significant. There is a large variation within degree of visual impairment and age. The results are therefore indicative but create the basis for values representative for people with visual impairments. Furthermore, the results suggest topics where precautions should be taken.

Results and discussion

The results for walking speeds horizontally and descending stairs and a discussion of these are presented in separate sections in the following. The sections are further divided into two parts;

- Free walking speed
- Walking speed dependent on density

In Denmark, visual impairments are split into four categories. The results for the two parts are presented for each of the four Danish categories of visual impairment - A, B, C and D.

In this study it is assumed that participants can walk unrestricted at their own walking pace when person densities are less than 0.54 $pers/m^2$. Person densities therefore restrict the limit for the free walking speed when greater than 0.54 $pers/m^2$. The results obtained in the experiments are compared with the empiric model presented by Nelson and Mowrer (N&M) in [PIV-7].

Walking Speed horizontally
The mean walking speed obtained in the experiments for category B, C and D are given in Table 6.2. Category A was omitted due to lack of data points. Comparing the results for the three categories it could be seen that the mean walking speed decreases as the vision is reduced. The same tendency applies for the observed minimum and maximum mean walking speed and the standard deviation. This shows that the vision loss has an effect on the walking speed. Recommended values for the free walking speed horizontally found in literature and national codes ranges from 1.19 m/s up to 1.34 m/s [PIV-6], [PIV-7], [PIV-8]. Comparing the measured free walking speeds from the experiments with the literature values gives that the mean value for people in category B is in the lower end of the range for able-bodied people. On the other hand, the mean values for people in category C and D are considerably lower than the suggested values for able-bodied adults. If the spread is then considered it is seen that for people in category B the full range found in the literature for able-bodied people is encompassed. Thus, the free walking speed for people in category B can be considered similar with able-bodied people. The spread for people in category

C do not cover the full range found for able-bodied people. Consequently it is not possible to confirm or deny the similarities with the free walking speed for able-bodied people. On the other hand the spread for the free walking speed for people in category D is not comparable with able-bodied adults because the interval does not encompasses any suggested values for able-bodied people.

Table 6.2: Mean free walking speed on horizontal planes for each of the four Danish categories.

Category	Mean $[m/s]$	Min $[m/s]$	Max $[m/s]$	Std. dev. $[m/s]$
A*	-	-	-	-
B (n=8)	1.18	0.58	1.72	0.39
C (n=8)	0.95	0.38	1.56	0.30
D (n=6)	0.75	0.35	1.09	0.22

* Only two data points available. Results are left out.

Figure 6.2 shows the horizontal walking speed as a function of person density for each of the four categories of visual impairment. In the figure each data point is shown together with a trend line formed as the best linear fit of results, where the person density is larger than 0.54 $pers/m^2$. Results for the Nelson and Mowrer-model (N&M-model) are displayed for comparison.

There are only few results for people in category A. However, these indicate that the walking speed for this group is more affected by an increasing density than able-bodied adults due to a steeper trend line. It is seen that when the person density increases the walking speed decreases more rapidly than suggested by the N&M-model. The explanation of this behaviour might be that people in this category still have some vision left and they are therefore able to register an increasing amount of people around them and might react on that.

Results for people in category B shows a large variation between the walking speeds varying from 0.39 m/s to 1.92 m/s. This indicates that people in this category have very different physical abilities and behaviour during the evacuation experiments, which affect their walking speed. Some participants in this group are able to uphold a walking speed larger than the suggested value for able-bodied, and is therefore unrestricted by their impairment. On the contrary others have walking speeds considerably lower than value suggested by the N&M-model. The trend for this category indicates that people in this group are able to maintain a higher walking speed while the person density increases compared with the N&M-model. Therefore the people in category B are not affected by an increasing number of persons around them to the same degree as able-bodied adults. However, the large deviations should be considered and

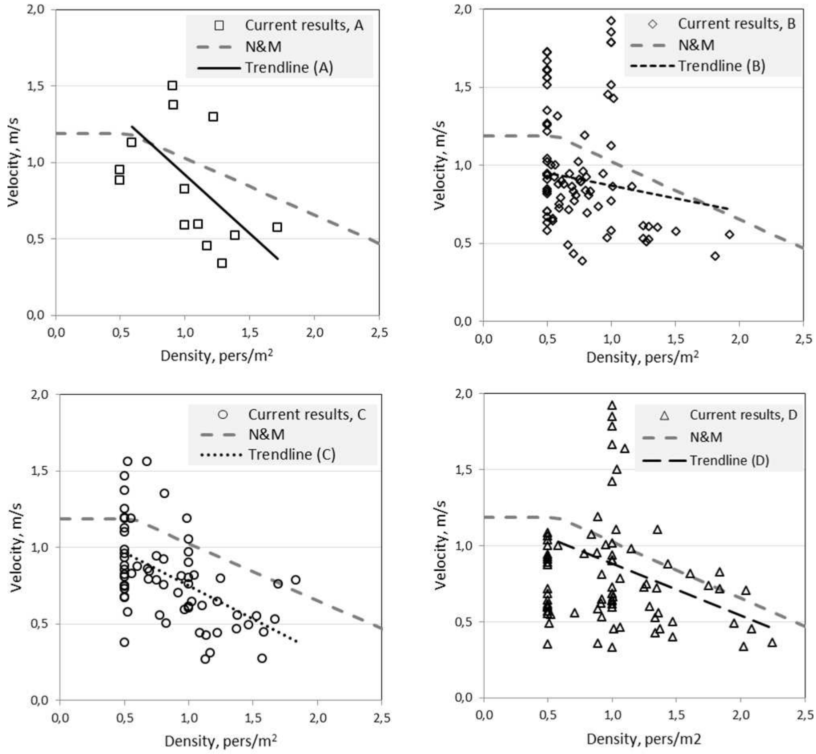

Figure 6.2: Relation between walking speed on horizontal planes and person density. Each of the four categories is represented with data points, trend line and the empiric N&M-model.

further investigated.

Studying the results for people placed in category C indicate a trend similar to the N&M-model. The walking speed horizontally decreases as the person density increases with a slope comparable with the N&M-model. However, the trend line is displaced downwards and the initial walking speed is less than the one for able-bodied adults. Furthermore, the data points are distributed more evenly around the trend line with the majority of the points lying below the N&M-model.

The walking speed of participants in category D decreases with density in a slope with an angle comparable with the one from the N&M-model The trend line is however displaced downwards as for people in category C and the initial walking speed is lower compared to able-bodied adults. The variation in walking speeds among the participants in this group is in the range from 0.33 m/s up to 1.92 m/s. Assessing the raw video footage material the outlier data points (seven points with walking speed larger than 1.4 m/s) can be explained by the behaviour of the assistants. Some participants are dragged by assistants, who almost were running during the experiment.

In common for the four categories are that the majority of the data points is situated under the empiric model presented by Nelson and Mowrer. This indicates that it is not conservative to apply the N&M-model for people with visual impairments.

It is of interest to directly compare the four trend lines for the different categories to see if the degree of vision loss influences the relation between the walking speed and an increasing density. The comparison is presented in Figure 6.3 together with the N&M-model. It is seen that the trend for category A has the largest inclination. On the other hand the inclination for trend line B is the smallest. The trend lines for category C and D lies between A and B. The slope for A, C and D intend to follow a trend where an increasing reduction in vision leads to a reduced inclination of the trend line resulting in a reduced density-walking speed dependency. Hence, the line gets more flat as the vision is reduced. Applying the mean error for the four trend lines will show that all four trend lines fall within the same range, which means that the degree of visual impairment will influence the relation between walking speed and increasing density. It is necessary to increase the amount of data in order to establish a more representative assessment of the influence of the degree of visual impairment on the relation between walking speed and density.

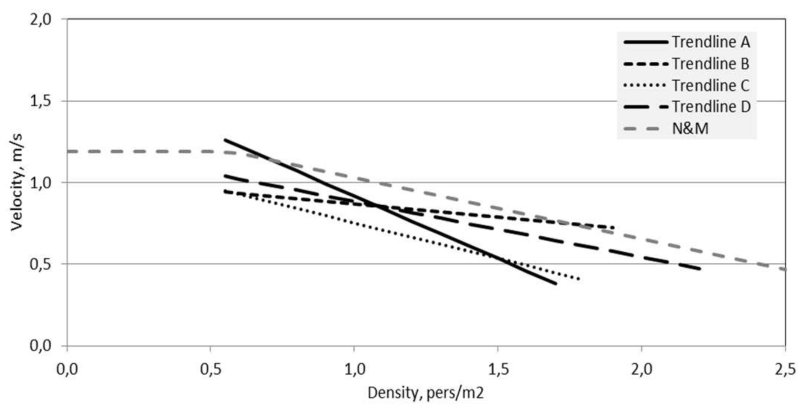

Figure 6.3: Trend lines for each of the four Danish Categories together with the empiric N&M-model for horizontal movement.

The physical ability and behaviour during movement is different for people with visual impairments compared to able-bodied people. People with visual impairments often use a mobility stick to orientate. Neighbouring people in the evacuation flow will notice the stick and the space it occupies. The application of a mobility stick might therefore affect the person density registered by the impaired person, because the stick will supply some free space even though she/he can feel the neighbouring people with the stick. Similarly a guiding dog will affect the physical ability to move during evacuation. The dog will be able to guide the visually impaired person to the door, the stair etc., which might lead to an increase in velocity, but will also be able to register other people around and might be affected by increasing person densities. Furthermore, literature contains little on the evacuation of animals. In this study it has not been possible to observe whether a dog slows down the handler or just continue with the same walking speed independent of the person density. Contrary, a person normally having a guiding dog will be further disabled without the dog, which might give reason to a reduction in their walking speed.

Walking speed descending stairs
The free walking speed descending stairs for category C and D are presented in Table 6.3. It has not been possible to obtain results for category A and B, because people in these categories have not been traveling on stairs. The results for walking speed descending stairs for category C and D do not differ from each other, which indicate that the free walking speed descending stairs is not affected by the degree of vision loss. Comparing the derived values for blind and visually impaired people with values found in national and international guidelines for able-bodied people show that the results are comparable to values used in Denmark and Sweden. On the contrary the mean walking speed for category C and D are lower than the value suggested by the N&M-model.

Table 6.3: Mean free walking speed descending stairs for category C and D.

Category	Mean $[m/s]$	Min $[m/s]$	Max $[m/s]$	Std. dev. $[m/s]$
C (n=3)	0.74	0.54	0.92	0.10
D (n=4)	0.71	0.58	0.91	0.09

The results derived from the experiments are obtained in buildings where the participants were very familiar with the environment and used the stairs on a daily basis and this might have influenced the results. The geometry and stair layout might also have influenced the results. All stairs were equipped with handrails on one or both sides, an important orientation tool for blind and visually impaired people.

The experiments provided very few results for the relation between walking speeds descending stairs and increasing density for category A and B, and these are therefore left out. The obtained results for category C and D are presented in Figure 6.4 together with a corresponding trend line and the N&M-model for stairs.

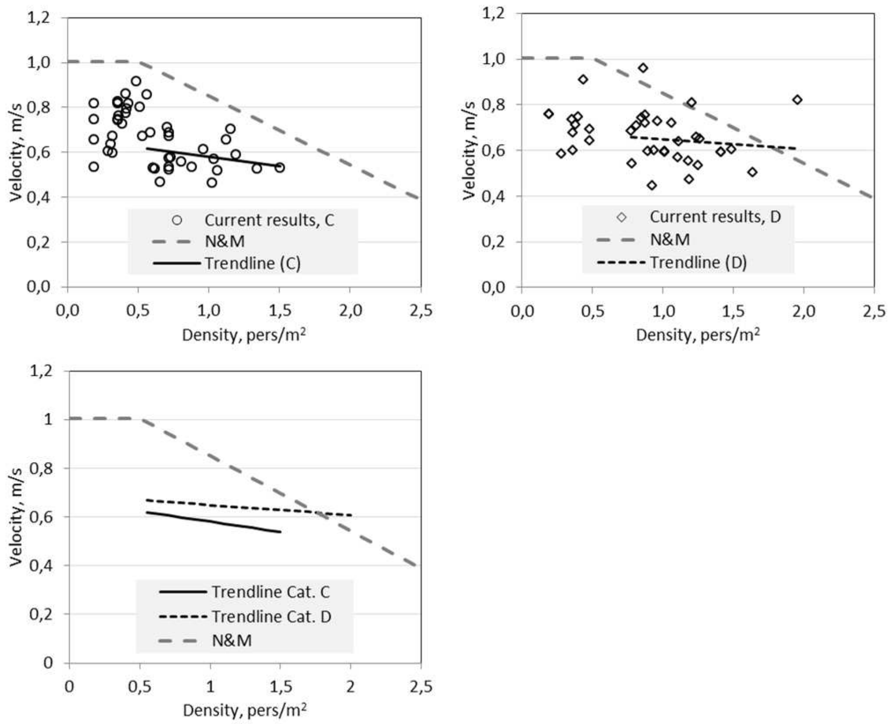

Figure 6.4: Relation between walking speed descending stairs and person density for category C and D. Data points, trend lines and the empiric N&M-model are displayed in the graphs.

All data points, for people in category C, lie below the graph from the N&M-model. Studying the trend line it is seen that the slope is less steep compared to the N&M-curve. In addition the initial walking speed is considerably lower than the suggested value for able-bodied people presented by the N&M-model.

The results achieved for people in category D show the same trend as for people in category C. Only three data points are situated above the empiric N&M-model. The trend line for category D also has a less steep slope compared with the curve from the N&M-model. In addition the trend line crosses the N&M-model. All these parameters and associated trend lines indicate that people in both category C and D are able to uphold a higher walking speed descending stairs even though the density is increasing.

Furthermore, a direct comparison of the trend lines for the two categories shows that the inclination decreases with increasing vision loss - thus people with the poorest vision have the highest walking speed even though the density is increasing. The initial walking speed for both categories is on the other hand considerably lower than for able-bodied people.

People with visual impairments do not orientate in the same way as able-bodied adults who use their vision as the primary source for orientation during evacuation. Non-visually impaired people therefore adjust their walking speed based on their vision as the density increases. Adjustment of the walking speed for able-bodied people is often done in advance to a queue in order to minimize the time standing in the queue. People with vision loss do not adjust their walking speed as a consequence of a queue in front of them before they actually meet the queue by register it with their mobility stick or physically feel people around them. A guiding dog might serve as a seeing connection to the surroundings and give a sign that a queue is formed in front and thereby reduce the walking speed before the visually impaired person physically register the queue. However, the interaction between the visually impaired person and the guiding dog is not investigated in this study.

Limitations
The experiments were carried out in the participants' natural environment and they were familiar with the surroundings. This might have influenced the results. To survey the influence of the familiarity with the environment interviews were carried out after the experiments. The interviews primarily assessed the participants experience with the evacuation experiments. The interview contained a direct question on how important the knowledge on the surroundings was in order to complete an evacuation. All participants answered that the knowledge of the surroundings was of importance and half of them that it was of high importance (not shown here). Hence, it might be expected that the walking speed horizontally and descending stairs would decrease if the experiments were held in unfamiliar environments.

The population involved in the experiment varies in age, gender and mobility capabilities. Some are able to walk without any aid, whereas others need a stick, guiding dog or physical assistance from a non-visually impaired person. It is not registered if the participants have other mobility limitations not associated with their reduced vision. Experiments comprising human beings will always involve natural fluctuations because it is very difficult for predict human behavior and this is reflected in the analysis and on the derived results.

Observations - Human behaviour and interactions
The participants' behavior was observed during the experiments. The most frequent observation was that the walls were used as guiding lines. The participants oriented themselves by placing their hands and fingers on the walls

with a light touch, just like the fingers were dancing on the wall. In the buildings, where wide corridors were a part of egress path, the walls were important for orientation. In addition, it was observed that the participants preferred to walk with the wall located on their right hand side. This way of orientating in the building increased the participants' ability to travel safely and to determine where they were. In some of the buildings the walls were equipped with special marks indicating different rooms or places, where extra attention was needed. In the experiments with stairs it was common that the participants used the handrails for orientation. In the cases where the width of the stair allowed for it, the participants used the handrail on one side and the opposite handrail or wall on the other side. This shows that handrails are an important tool for orientation for blind and visually impaired people while walking on stairs. Using the walls for orientation, the handrails in the stairs, and the marks are all contributing factors for the participants to feel more comfortable and secure in the building environment and during an evacuation.

Participants walking alone slowed down if they registered an obstacle placed in their way. The distance to the obstacle was short at the time for noticing it because the participants needed physical contact with the particular object. Actually some participants stopped completely when maneuvering around the object. People with no visual impairments would have been able to adjust their walking path in advance to avoid the obstacle. Thus, this is not a possibility for people with visual impairments. However, for this group of people it is very important to keep the egress paths clear of any obstacles because obstacles will lower the capacity of the egress path and thereby affect the evacuation flow and time.

Different behavior was observed depending on whether the participants were walking alone or in groups. The behavior observed among participants walking in groups showed a strong personal relationship among the participants. The participants were waiting and felt responsible for each other. Furthermore, the ones with the best vision assisted the ones with a more poor vision by e.g. holding doors and lending a helping hand. In some cases participants were returning into the building to assist the ones who were lagging behind. This affiliation is problematic and could cause dangerous situations in a real emergency. It is assumed that parts of the behavior were caused by the instructions given prior to the experiments and the fact that the participants knew each other beforehand. However, it is anticipated that the observed personal relationship also would occur even though the participants did not know each other beforehand, because they would be aware of each other's difficulties.

During the experiments it was in addition observed that some participants were holding their ears due to a very loud alarm signal. This behavior might not be the most optimal way of moving during evacuation. However, people with visual impairments do not have a better hearing compared to able-bodied adults, but their senses might be sharpened due to training. Bad behavior as running during evacuation was observed. In the given case a visually impaired participant was forced to adopt this running behavior by a non-visually impaired assistant.

Conclusion

Evacuation characteristics for blind and visually impaired people are presented in the current study. The free walking speed for densities less than 0.54 $pers/m^2$ on horizontal planes and descending stairs were presented. In addition the relationship between walking speed and increasing densities were investigated. The study also gave results on the characteristic behavior for people with visual impairments during an evacuation.

The mean free walking speed descending stairs is studied and presented in this paper. However, only results for category C and D are available. The derived values for these two categories are very similar and comparable with values found in Danish and Swedish guidelines. The mean free walking speed descending stairs found in the current study is not dependent on the degree of vision loss and is comparable with able-bodied adults.

Results for the relation between the walking speed and an increasing density shows that the walking speed is not affected by an increasing density to the same extent as able-bodied adults. People with visual impairments are able to uphold a higher walking speed descending stairs than able-bodied adults even though the person density increases. However, the initial walking speed is lower than the value suggested by the N&M-model.

Results for the mean free walking speed horizontally showed that the speed depends on the degree of vision loss. The more poor the vision, the lower the mean free walking speed. Comparing the values for the visually impaired persons with able-bodied adults showed that people in category B has a similar walking speed, whereas people in category C and D have a lower walking speed. It is therefore not possible to assign a single value for the mean free walking speed on horizontal planes for all visually impaired people. In addition it is not conservative to use the value for able-bodied adults.

The relation between the walking speed horizontally and an increasing density was investigated for participants in all four categories. The results show that the relation is dependent on the visual impairments. However, it could not clearly be shown that the density dependence of the horizontal walking speed is influenced by the vision loss. Further investigations are needed to clarify how the density dependency affects the walking speed for increased vision loss, a relation seen when descending stairs. In common for the four categories are that the majority of the data points are situated under the N&M-model for able-bodied adults.

The observations carried out during the experiments showed that the design of the building environment is important for the ability to orientation for people with reduced sight. Walls and handrails are in particular important for the orientation possibilities for people with visual impairments. Furthermore, obstacles placed in the egress path were identified problematic for this group of people. People with visual impairments are not able to adjust their walking path in advance to avoid the obstacle because they need physical contact with the object to register it. There was observed a large responsibility for each other among the participants in the experiments and the ones with the best vision assisted the ones with more poor vision.

The findings presented in this article show that evacuation characteristics for people with visual impairments are not comparable with able-bodied adults. Walking speeds horizontally and descending stairs and the behavior are different compared to able-bodied adults with no impairments. On the basis of the presented study it is recommended to be aware of the composition of people in a building while designing the safety and performing calculations of the total evacuation times. Furthermore, results from this study contribute to a more sustainable building design by enabling fire safety engineers to enhance the egressibility for people with visual impairments. However, more data is needed to confirm and verify the indicative findings from this study.

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Chapter 7

Summary of Findings

The following chapter highlights the findings obtained through the experimental program. The results presented in this chapter constitute an overview of the results presented in the papers and are supplemented with additional findings from appended publications and reports. The chapter is divided into sections representing different aspects of the evacuation process from buildings and other structures.

7.1 Presence in Buildings

Data on vulnerable people's presence in different building types were investigated through interview surveys conducted in parallel to the evacuation experiments as described in chapter 2. Interviews were conducted with visually, hearing and mobility impaired participants as well as the elderly. Findings are presented in chapter 4 and appendix K.

The respondents were asked to think of and identify four types of buildings, which they visited besides their home. Based hereon, it was found that the majority of respondents identified transport terminals, shopping/grocery stores, office buildings, and restaurants as building types they visit. Besides these building types the following buildings were also mentioned; sport facilities, hotels, concert venues, apartment buildings, educational buildings, library, and medical facilities. Thus, a large variety of buildings were mentioned by the respondents, indicating that vulnerable people are present in almost all kinds of buildings and structures.

The frequency of visits were also assessed. It was found that the four type of buildings mentioned by the majority of respondents were visited either daily or weekly. The frequency of visits for the remaining buildings varied from daily to annually, dependent on respondents and the building type. The outlined trend suggest that vulnerable people are present in almost all kind of buildings. Hence, it is necessary to analyse who the users of a building are, and then design the building according to the occupant characteristics. Considering relevant sub-populations in the design phase can ensure equal safety for everyone.

7.2 Walking Speed - Horizontal Planes

Results for the walking speed on horizontal planes were obtained for low densities, where people are able to move independently, and for higher densities, where people are affected by each other. Low densities can be defined as person densities equal to or less than 0.54 $pers/m^2$ according to the N&M theory, [67]. In the train-tunnel experiment (RESC) free unimpeded walking speeds were collected when participants entered the tunnel and density dependent walking speeds for the different sub-populations were collected during evacuation of the train-tunnel configuration. Results were obtained for able-bodied people, elderly and children as well as participants with hearing, cognitive, mobility and visual impairments. In the experiments focusing on blind and visually impaired individual's walking speeds horizontally were obtained in both low and higher density areas. Likewise, the degree of visual impairment was taken into consideration.

In the train-tunnel experiment (RESC) the mean free walking speed was determined for each of the seven sub-populations. Assessing the results, it is found that the children and hearing impaired participants had the highest mean walking speed and the participants with mobility impairments had the lowest mean walking speed. The average free speed for children was 1.89 m/s and 1.81 m/s for the hearing impaired participants, see table 5.2, thesis paper III chapter 5. Overall, the individual walking speeds ranged from 0.35 m/s for the slowest participant and up to 2.76 m/s for the fastest person. Both extremes were obtained by the cognitively impaired participants. The mean free unimpeded walking speed, suggested in guidelines for able-bodied adults, is in the range from 1.19 to 1.3 m/s, [20, 67–69]. Comparing the mean values obtained for the different sub-populations with values from guidelines, it was found that the majority of results was above the suggested value. Only the mean unimpeded free speed for the mobility impaired participants was lower than that suggested in guidelines. However, the sample is too small statistically, and the obtained results are only indicative and should be used with precaution. The free unimpeded walking speed, from the train-tunnel experiment, were primarily used as input to an evacuation model. The evacuation model was constructed using the software STEPS and a summary of results are presented in section 7.5.

The train-tunnel experiment also gave results in the higher density area, where the walking speed is affected by the surrounding person density. There was found a good correlation between the experimental results for the able-bodied adults and the corresponding theory developed by Nelson and MacLennan. For the elderly and mobility impaired participants the theoretical N&M model was not on the conservative side. The influence of the density on the walking speed was more distinct for the hearing impaired than that given by the theory expressed by a larger gradient for the trend line. The opposite was found for visually impaired individuals, who were able to maintain their walking speed, expressed by a small gradient, even though densities were increasing. Comparing results for main and transversal tunnel, it were found that all results were generally shifted to the left. Analysing the shift, it was found that it was caused by the physical representation of the reference area used in the density calculations. Furthermore, it is suggested, based on the shift and analysis of recordings, that the walking speed is not only affected by the surrounding person density, but also on the method applied for density calculations. The number of individuals in the studied person's point of view might have a larger effect on behavior and walking speed than individuals outside the person's point of view, even though they contribute to the density calculation.

The results obtained for the visually impaired participants showed that the mean walking speed was dependent on the degree of visual impairment. The common trend found in the experiments indicate decreasing walking speed for participants with increasing loss of sight. Furthermore, participants assisted by a guide dog had a higher walking speed than participants not accompanied by a dog, see appendix K. The physical shape of the participants is assumed also to affected the results. Comparing the experimental results with theoretical values for able-bodied adults, it is found that people with visual impairments have a lower free unimpeded walking speed. In addition, this segment of the population often use a walking aid and therefore takes up more space during movement. The results obtained for densities above 0.54 $pers/m^2$ were compared with the theoretical model developed by Nelson and MacLennan (the N&M model). It is found that the majority of data points are situated below the N&M curve, indicating that application of the theory for able-bodied people will provide non-conservative estimates. The results likewise indicate that the poorer the vision the less affected are the individuals' walking speeds by increasing densities.

The overall trend found in the experiments, for the walking speed on horizontal planes, was that the common theory for able-bodied people cannot be applied for other segments of our population. Hence, it is important to be critical, while using data from guidelines and literature and pay special attention to characteristics of the occupants.

7.3 Walking Speed - Stairs

The experimental program likewise revealed results for the walking speed descending stairs. These results are also dependent on person density. For stairs the low density area is, like for horizontal planes, defined as a person density equal to or less than 0.54 $pers/m^2$ according to [90].

The geometry of the stair in the train-tunnel experiment implied that results for the low density area were not obtained. The reason was that the stair only contained three steps and had area of 0.88 m^2 giving a density of 1.1 $pers/m^2$ with one person on the stair. As illustrated for the relation between walking speed and density on the horizontal, the reference area have considerable influences on the results. The results obtained in the higher density area for the various subpopulation in the train-tunnel experiment shows that the Nelson and MacLennan curve was a conservative estimate for the able-bodied and hearing impaired people. On the other hand, the N&M curve over-estimate the relation between walking speed and density for the mobility impaired test persons, shown by a trend line situated below the N&M curve. For elderly, children, cognitive, and visually impaired participants the trend lines cross the N&M curve indicating a reduced density dependence compared with able-bodied people. The first part of the trend line lies below the N&M curve and ends above the curve. The intersection between the two curves are observed for densities in the range 1.4 $pers/m^2$ to 2.25 $pers/m^2$.

For the visually impaired test subjects it was found that the walking speed descending stairs was comparable with values suggested for able-bodied people. The walking speed ranged from 0.16 m/s and up to 0.92 m/s. The values suggested in literature range from 0.7 m/s to 1.05 m/s dependent on stair geometry, [90]. It was not possible to identify any influence of degree of visual impairment on the walking speed descending stairs. Walking speed for the participants with the poorest vision was not significantly different from the ones with the best vision and vice versa. There was neither found any difference between people, who were accompanied by a guide dog and those who were not. The results found for increasing densities show that the vast majority of data points were situated below the theoretical curve for able-bodied people suggested by Nelson and MacLennan. The trend lines representing the data indicate that the visually impaired participants were able to maintain a roughly constant speed descending stairs. However, the density area in which the results were collected only reaches 2 $pers/m^2$. This fact might explain why a decrease in walking speed for increasing density was not observed. It is reasonably to presume that at higher densities, where people have physical body contact, people with visual impairments will also be affected.

Generally, the free unimpeded walking speed descending stairs shows that people with low vision had a similar walking speed compared to able-bodied people. Nonetheless, for increasing densities the N&M curve is not representative for all the tested segments of the test population.

7.4 Human Behavior

All experiments were recorded with video cameras and the human behavior occurring during the evacuation experiments was registered. The overall impression of all experiments was that the participants behaved calmly and according to the instructions they have received. All participants knew, they were participating in a simulated emergency. It is assumed that, that might have influenced their behavior.

In the experiments with heterogeneous groups (RESC) the participants demonstrated an altruistic behavior, where children were encouraged by adults and elderly to step in front of them. In addition, there were numerous examples of participants lending a helping hand to another participant or assisting the other person to traverse the steps from the train to the tunnel. Regarding social influence, the instructions implied that all participants beforehand knew that they were supposed to exit the train. They did not have to interpret the situation and warning message before they could decide on an action, they already knew the overall goal.

In the experiments involving homogeneous groups of people with visual impairments, it was found that this segment of the population walked close to walls and other guiding lines. However, difference was observed between the participants assisted by a guide dog and those who were not. The participants with guide dogs had a tendency to walk closer to the centerline of corridors, whereas participants without a dog relied on enclosing building elements, e.g. walls and banisters, for orientation. It was clear from the footage that the participants with best vision assisted the ones with a poorer vision, for instance by holding doors for each other.

The movement path found for the visually impaired participants, where they walk close to walls and other enclosing building elements during evacuation, is likewise found in studies assessing able-bodied peoples behavior and movement through smoke, [91, 92]. When normal-sighted people move through a smoke filled environment they will experience a degree of vision loss. In order not to loose their orientation they move along lines that they believe, will guide them to an emergency exit. Consequently, peoples' walking speed decreases as a function of visibility. For a visibility of 1.39-1.11 meters the mean walking speed is 1.00 m/s which is comparable with results found in thesis paper IV (chapter 6 for participants who have severe vision loss, [86, 93]. People with visual impairments might therefore have an advantage compared to normal-sighted people in a smoke-filled environment, because they are used to navigate by other means than the sight.

A few instances of competitive behavior was observed. One instance was observed in the experiments with only visually impaired test subject and a one instance in the tunnel experiment where the children were competing in getting out first. However, people generally demonstrated an assistive and altruistic behavior.

7.5 Evacuation Modelling

The free unimpeded walking speed and reaction times for the seven subpopulations found in the tunnel experiment served as input to the STEPS model. In STEPS the train-tunnel configuration was modelled and total evacuation times as well as individual evacuation times were extracted. A good correlation was found between the total egress time predicted by the model and the experimental results applying the speed/distance relation for the homogenous group of able-bodied people. The same correlation was not found for the heterogenous groups applying the speed/distance relation. The software suggest an additional relation for walking speed reduction called the speed/density approach. Applying the speed/density approach gave the best prediction of the total egress times for the heterogenous groups.

It is worth noticing the differences in total evacuation time for the homogeneous and heterogenous groups. The total time to exit the experimental setting for the heterogenous groups was twice the time for the homogenous group only comprising able-bodied adults. This fact indicate that the composition of the building population is crucial for the egress time. It is consequently important that the fire safety engineer, when selecting input data for evacuation modelling, is very cautious and selects data that represent the characteristics of the building occupants.

7.6 Building Design Challenges

An important factor for a successful evacuation is the design of the egress path. As a part of the interview study the participants were asked to identify building and design elements that restrict their use of the building. Many of the identified components likewise are a part of the egress path. If a person experience difficulties during normal use, they will probably experience the same difficulties in an emergency.

The respondents identified stairs as causing difficulties. One of the issues with stairs was inappropriate marking of the edges, making it difficult determine where the edge of each tread is and where the stair ends. Another issue concerning stairs was handrails - whether the stair was provided with handrails and how these were designed. The visually impaired respondents pin pointed that a continuous handrail in staircases with more than one flight was preferred. A continuous handrail will make sure that the visually impaired occupant does not lose orientation during movement on the stair. The beginning of the handrail is also essential, since it is related to the beginning of the stair. If the handrail starts some distance before the first tread, it is easier for the person to find the stair and feel comfortable with it.

The interview study revealed several options for improvement regarding the layout of the building, with regard to fire safety for people with visual impairments. The suggestions were:

- Intuitive building layout
- Sufficient lighting
- Recognisable and "easy to find" emergency exits
- Avoid obstacles in the egress route

For a visually impaired person it is easier to follow a predictable and intuitive layout of a building with even surfaces, and easy identifiable exit paths, than a complex layout without any guiding lines. Lighting condition is another important factor to ensure an efficient evacuation for people with visual impairments. For instance, it can be difficult to identify possible egress routes from a dim room for a visually impaired person, and there is an increased chance of missing an emergency exit door in a corridor, if the level of lighting is insufficient, [94]. During an emergency normal sighted people would also benefit from a well lit egress path. Furthermore, the egress path and specifically doors in the egress path should be easy to recognize as an emergency exit. A possible way of doing so could be to apply different texture or color on the door. Obstacles, for example furniture, are also identified as a challenge for visually impaired people. Due to their reduced vision they often bump into obstacles because they cannot adjust their walking path based of their sight.

Information systems are essential during an emergency to warn and instruct people. An information system can consist of both audible systems and signage systems. Regarding audible systems the visually impaired respondents claimed that the sound level is crucial for their ability to navigate via back ground noise. If an alarm is too loud people with visual impairments loose their ability to navigate using sound. People with visual impairments are actually able to "hear" an open door. Normal flat signs are good for normal sighted people but are barely accessible for people with visual impairments. Therefore accessible information is important to consider also in an emergency perspective. Size of letters, raised letters, contrasting colors, tactile information could all be ways to improve the accessibility of information to visually impaired people.

A study conducted in Sweden investigated the challenges people with disabilities meet in the built environment [95]. In accordance with the findings from the present interview study the Swedish study likewise found that the building design should be easy to comprehend, and that stairs should be designed properly. Furthermore, opening devices were identified as problematic. It was hard for respondents to manoeuvre two-hand grips to open emergency doors and windows.

Currently there exists legislation and guidelines related to accessibility of a building, however no standards outline how to design e.g. an emergency door in a way that makes it easy for every one to operate without regard for disabilities.

7.7 Limitations

The experiments conducted throughout the PhD study provide findings and results that are restricted by some limitations. Performing experiments comprising human beings will contain an unknown element since prediction of human behavior is not always possible.

The experiments were carried out in both familiar and unfamiliar environments. Participants performing experiments in a familiar environment might have been more confident with the situation which might have affected their performance. Evacuating in a familiar environment, the participants might walk faster because they know where to go. On the other hand, participants performing experiments in unfamiliar environments might be more cautious because they might be in doubt where to go and what to expect along the egress route.

Another aspect that might have influenced the outcome of the experiments was a possible lack of realism in relation to an emergency situation. In the instructed and partial evacuation experiments the participants knew what to do and where to go. Their walking speeds might therefore not fully reflect their performance during a real emergency. However, it is nearly impossible to collect data on quantitative measures during real emergencies, because predictions on where and when cannot be made. It is easier to collect qualitative data e.g. behavior from real incidents, based on witness testimonies, and interview and questionnaire surveys from survivors.

All experiments were documented using video footage, which entail both advantages and disadvantages. On the positive side, it is possible to review the evacuation experiments over and over again and focus on different aspects of the evacuation. Negatively, the experiments were conducted in natural environments and cameras were positioned where possible. In natural environments, it is not possible to control all parameters. For example lighting conditions have been a challenge, if the setting was too dark, it was difficult to identify each and every participant. The number of available cameras restricted how much of the egress path that could be covered and documented. Hence, some data might be lost. Conducting field experiments in participants' natural environment limit some factors but on the other hand encourage participants to behave naturally where they are less influenced by e.g. measurement equipment. Experiments conducted in a laboratory setting allow full control of lighting conditions, egress path, camera positions, participant identification etc.. However, the participants might not behave naturally. None of the experiments conducted throughout the PhD study were carried out in a laboratory setting, but as field experiments. However, the participants were instructed in what to do in the announced experiments. Hence, the results and finding were obtained in a combination of field and laboratory experiments.

The analysis of data was carried out manually. The egress routes in the experiments were covered with numerous cameras and none of the available tracking software could recognise a person from one camera to another. The available software did not meet the requirements needed for analysis of the current work. Passage of e.g. check points along the egress path was therefore subjective judgement and was related to the person analysing the data, and two persons might judge differently. To reduce the subjective factor strict rules were setup on how to analyse the data and as far as possible the same person analysed a complete set of data to minimize the subjective factor.

The results and findings extracted from the experiments is based on a relatively small sample and are therefore only indicative trends. In order to increase the statistical significance of the results a larger test sample are needed. Nevertheless, available data in literature are limited and a small amount of data indicating trends are better than guessing.

All participants, except the ones participating in the unannounced full scale experiments (SR 1+2), completed more than one trial in the same experimental setting. It might therefore be argued that the results are biased by a training effect. In the experiments conducted in the train-tunnel setting (RESC) participants were seated randomly in all trails trying to reduce the bias. In the experiments conducted in Washington D.C. (WDC) and at the Danish Association of the Blind (DB) groups were assembled differently in all trials and participants maximum conducted two trials with the same fellow participants. The experiments conducted at location A (IBOS 1+2) the participants did not use the same egress route twice to reduce the training effect. Some participants had a personal relation prior the experiments that likewise might have affected their behavior during the evacuation experiments. However, social behavior is also found in real incidents.

Chapter 8

Concluding Remarks

The aim of the PhD study was to increase the knowledge about evacuation of heterogeneous populations, with a special focus on blind and visually impaired people. Seven different experiments were conducted as a part of the experimental program enclosed in the PhD study. The experimental study gave the following answers to the hypothesises outlined in the research objective (section 1.4).

- The study confirms that people with various disabilities visit all kind of buildings. Hence, their safety in case of an emergency should therefore be equal to the safety of able-bodied people.
- Walking speeds for people with impairments have shown to be different compared to able-bodied people. The N&M theory was confirmed for able-bodied people and was a conservative estimate for hearing impaired people descending stairs. Likewise, the N&M theory gave a conservative estimate for cognitive impaired people and children walking on horizontal planes. An increased person density have shown to decrease the walking speed, which is seen for all the tested sub-populations.
- The individual reaction time was found to be affected by social influence. The effect was most distinct for participants seated close together in the same seating group. There was not found any correlation between reaction time and sub-population. However, the hearing impaired individuals reacted upon others reaction due to lack of an accessible warning format for this sub-population.

- In the train-tunnel configuration the total egress time for the groups comprising different sub-populations was twice the time as for a reference group consisting of only able-bodied adults. Hence, total evacuation times were highly affected by the composition of the evacuees and their evacuation characteristics.

- There was observed an altruistic behavior among participants in the evacuation experiments comprising heterogenous populations. The same behavior was not observed for experiments only involving able-bodied adults.

- Blind and visually impaired people have on average a lower walking speed horizontally and a comparable walking speed descending stairs compared with able-bodied adults.

- The preferred movement path for blind and visually impaired was along walls and tactile surface lines. Walking along these lines allows the visually impaired to navigate and orientate in the egress route.

- The walking speed for visually impaired people depends on the degree of vision loss. The poorer the vision the lower was the free unimpeded walking speed. However, for increasing person densities individuals with the poorest vision were less affected and could maintain a higher walking speed. The better the vision the more affected were the individuals walking speed by the surrounding person density.

- The outcome of the interview survey revealed that common parts of the egress path e.g. stair, constitute challenges for the vulnerable segment of our population.

8.1 Future Work

As indicated in the literature review, carried out in the introduction, only a limited amount of data are available describing the evacuation characteristics of vulnerable people. Although, this study contributes to an increase in the available data more research is still needed to create a substantial foundation that can ensure equal safety for everyone. It is suggested, based on the findings in the PhD study, to move along two tracks for future research within the topic of evacuation safety for everyone.

The first track to follow is to conduct more experiments focusing on the heterogeneity of the tested population. Thus, establish more knowledge about the mechanisms that control evacuation flows, both in terms of quantitative measures such as walking speeds and flows, but also in terms of human behavior and interaction between individuals. Specifically, the suggestions are:

- more evacuation experiments conducted in different building configurations and with a carefully selected test sample that represents the diversity of society in means of representation of different sub-populations. The aim could be to investigate the influence of the composition of the test sample on important evacuation parameters such as walking speeds and density.
- to conduct unannounced evacuation experiments in natural environments and afterwards carefully register characteristics of the sample.
- further investigate how human behavior and interaction between evacuees with different disabilities affects an evacuation flow.

The second track suggested, is to increase the amount of knowledge regarding evacuation safety for blind and visually impaired individuals. Generally speaking, there is a lack of evacuation data for all types of disabilities, but the track suggested here is based on the findings revealed from the studies of the group of visually impaired people. Based on the findings, several interesting aspects concerning fire safety for blind and visual impaired people could be a frame work for further research. It is suggested to:

- investigate the influence of and improve technical installations for better orientation abilities for blind and visually impaired people during an evacuation,
- investigate how the building design can assist blind and visually impaired to a safe, easy and quick evacuation. Specifically, with focus on design of handrails and emergency staircases, configuration and marking of the egress route, as well as differences in textures and contrasting colors to enhance means of orientation.
- further investigate the influence of increasing person densities on the walking speed, both horizontally and descending stairs.
- develop cognitive maps and training programs for blind and visually impaired people to increase their preparedness and performance during an evacuation situation.

It is emphasised that focusing on a specific group of disabled people and their requirements in an evacuation situation might lead to compromises - what benefit one group might be a hinderance for another group. An inclusive building design is thus a compromise between different requirements outlined by occupants with different characteristics.

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Appendix A

Evacuation of mixed populations from trains on bridges

Type	Conference Paper
Title:	**Evacuation of mixed populations from trains on bridges**
Author:	C. Kindler, J.G. Sørensen and A.S. Dederichs
Conference:	6th International Conference on Bridge Maintenance, Safety and Management
Date:	July 8-12, 2012
Location:	Stresa, Italy

Abstract

An understanding of human evacuation dynamics and performance are important when designing complex buildings such as bridges and when applying performance-based codes in order to reduce the risk of exposing occupants to critical conditions in case of fire. Literature provides a number of case studies of real fire incidents as well as experiments concerning fire and evacuations. The majority of previous studies deals with the evacuation behavior of homogeneous groups and applies normative standard. However, a significant part of the population is poorly described such as are people with impairments which are about 10%-21% of the world's population, furthermore a mixed population comprehends elderly people, giving an additional 10%. In Denmark 20% of the population are aged below 15 years. In recent years a series of studies have focused on a broader population for experiments and models. The discussion of "equal access" is only followed slowly by the demand on "equal egress". However, the passengers on trains on bridges are rarely homogeneous mixture. At the same time equal egress is far from assured today.

This paper is on the evacuation of mixed populations from trains on bridges. The populations applied in the experiment are mixed according to a composition corresponding to the population of Denmark. The study has the following findings: the total evacuation times increase with a factor 1.5 when accounting for a mixed population comprehending a variety of age and impairments. The seating of the people in the train affect these times. More real data on subgroups of a mixed population are needed as input and validation data for models like STEPS.

Introduction

An understanding of human evacuation dynamics and performance are important when designing complex buildings such as bridges and applying performance-based codes in order to reduce the risk of exposing occupants to critical conditions in case of fire. Around the world bridges and tunnels are used as a part of the railway transportation system for both passengers and freight. Accidents in these complex structures, which are difficult to evacuate, are numerous (Skarra, 1997) (Fridolf, Nilsson, & Frantzich, 2011), e.g. Mont Blanc tunnel (Voetzel, 2002), Kings Cross Station Fire in 1987 (Donald & Canter, 1990). There are similarities in the two types of buildings with respect to installations (Rozorea, Calinescu, & Arghiroiu, 2006) and precautions for evacuation in an emergency situation, in spite the fact that one is above ground level and the other is below ground level. Emergency situations on this type of complex buildings imply scenarios of either cars or trains. The focus of the present study is evacuation from trains. The design can vary; it can consist of gravel path at height of the rails (Grindrod, Welch, & Fridolf, 2011) or a platform (Great belt Connection, Øresundsconnection). These platforms constitute an important element in the evacuation process and it is assumed that this element gives the necessary connection between the two types of constructions.

Guidelines on action to be taken by the staff in case of emergency do not include comprehend the evacuation capability of the passengers (Banedanmark, 2010). In the Danish Safety Guidelines for Trains is stated that wheelchairs and luggage are to be left behind in the trains in case of an evacuation. There are no instructions on the evacuation and the different needs during evacuation of the passengers. No special measures on the aid for passengers with impairments. There are no instructions on how to evacuate the passengers from the wheelchairs. Only limited results for passenger's evacuation ability from trains are available and the majority of the studies focus on evacuation from buildings (Damen, de Boer, & de Kloe, 2008). The performance of the evacuees in a building is considered different compared to trains because the characteristic and design of a train is very different from a building (Capote, Alvear, Abreu, Cuesta, & Alonso, 2011). The design of trains differ from the design from buildings the aisles are more narrow, steps are steeper and narrower compared to buildings. The limited data that exists on the evacuation characteristics for trains operates with a homogenous test population of able-bodied people (Frantzich, 2000)(Rozorea, Calinescu, & Arghiroiu, 2006). However, a significant part of the population is poorly described such as are people with impairments which are about 10%-21% of the world's population (Bendel, 2006), furthermore a mixed population comprehends elderly people, giving an additional 10% (Bendel, 2006). In Denmark 20% of the population are aged below 15 years (Danmarks Statistik, 2011). In recent years a series of studies have focused on a broader population for experiments and model (Larusdottir & Dederichs, 2010). Applying data on able-bodied people leads to non representative results for the population as a total and the characteristics for train passengers. Furthermore, studies have shown that a considerably part of the population have a temporarily or permanent kind of disability, and this part is more likely to suffer during emergency situations (Manley, Kim, Christensen, & Chen, 2011). To ensure that trains are designed to provide the same level of safety for all passengers, it is important to consider the composition of the population and to include the more vulnerable part. It is important in the design phase, but also when guidelines for evacuation are developed.

The discussion of "equal access" (Steinfeld, 1979) is only followed slowly by the demand on "equal egress" (Proulx & Pineau, 1996). At the same time equal egress is far from assured today (Diament, 2009).

New demands in society (WHO) imply the inclusion of people with disabilities so they are less restricted by their impairment. Hence, accessibility to and applicability of the same facilities in society as able-bodied people is required in spaces as public transportation system, buildings with a public purpose (libraries, theatre etc.) or workplaces (Shakespeare, 1993). This change originates partly in the increasing focus on accessibility among designers, engineers, interest groups and politicians.

The purpose of the current study is to investigate differences in the evacuation process from a train in a tunnel for homogeneous populations and a heterogeneous populations corresponding to the demography of Denmark. The scenario presents a similar scenario to the evacuation of a train on a bridge. The evacuation from a train is modeled with the software STEPS, where it is possible to assign different walking speeds for the passengers. The question is what is the effect of the composition of the population on the evacuation times. The results for the evacuation process in a train are considered relevant for bridges due to similarities in the structural design of the emergency paths.

Method

The evacuation is modelled and simulated with the evacuation simulation program STEPS. The basis for the simulation is a training facility placed in Korsør, Denmark. The facility is used for safety education of train stewards and personnel operating in the Great Belt tunnel and the design therefore corresponds to the Great Belt tunnel. The tunnel is designed as a twin tunnel with two parallel pipes. The pipes are interconnected for every 250 m with cross tunnels (DSB). In case of an emergency people in the exposed pipe are evacuated to the neighbouring pipe through these cross tunnels. The other pipe is then considered as a safe place and from where they are able to leave the tunnel. Passengers in the train is supposed to evacuate to the non-exposed tunnel pipe through the cross tunnel and the simulation is aborted while reaching the door to the other tunnel pipe. The floor-plan of the train, platform and cross tunnel is shown in figure A.1.

The train carriage has 20 permanent chairs placed in groups of four with a small table in between, three 'fold out' chairs are placed near the entrance to the brougham. The distance between the armrests on the permanent chairs are 0.55 metres. The door from the brougham to the aisle has a width of 0.74 metres while the outside passenger door has a width of 1.25 metres at the narrowest place. The distance from the exit door to the cross tunnel running parallel to the train is 4.4 metres and the cross tunnel has a length of 6.82 metres.

The stairs from the carriage to the passenger evacuation platform is three steps high, where the last step is on par with the platform. The vertical distance from the floor level inside the train carriage to the platform is 0.60 metres. The platform and the cross tunnel are in the same level. A sketch of the stairs is shown in figure A.2.

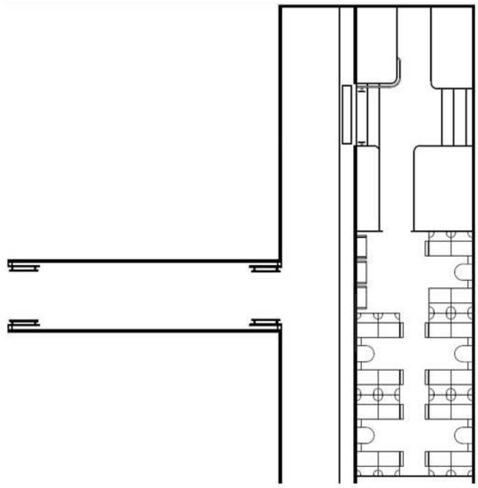

Figure A.1: Plan of the experiment facilities

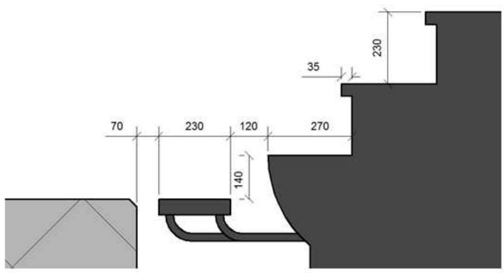

Figure A.2: The stair from the train to the platform

Building the model in STEPS

STEPS is a simulation program based on a discrete cellular automata model, with a basic assumption on only one person in each grid cell. The size of the grid is determined on the basis of the projected area an adult occupy of the floor area. From previous studies it is given that the projected area of an adult is 0.46 metres in summer dress and 1.1 metres if baggage is included (Predtechenskii & Milinskii, 1978). Since this is a simulation of an evacuation, people should leave their baggage behind, and a grid size of 0.5 metres is chosen. Hence, the space between people is considered. Due to the chosen grid size the maximum person density in the simulations are 4 pers/m^2, no matter if the persons are sitting in wheelchairs or considered as children. This makes the velocity of each person very important, since this is the parameter that has the biggest influence on the total evacuation time.

In STEPS a grid cell is either blocked or free, which induce the need to slightly change in the train dimensions so aisle, passages between the armrests, and doors fit with the grid of 0.5 metres. The slightly changed design of the train and the grid gives a maximum passenger capacity of 52 persons. The changed dimensions of the train, the grid and the original dimensions are shown in figure A.3.

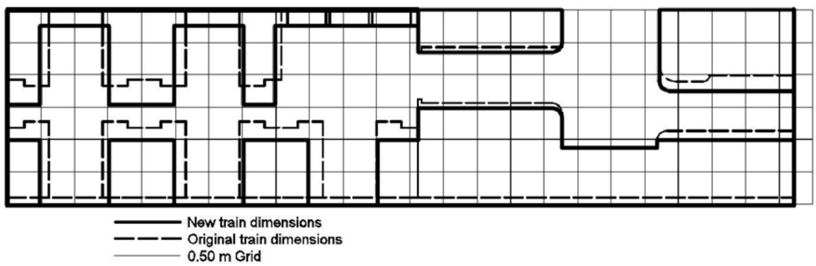

Figure A.3: Modified train dimensions (straight) and the original dimensions (dotted)

As indicated in figure A.3, the stair is not drawn in the plane of the train. In STEPS a stair is a plane in itself. The stair is defined as starting 0.17 metres from the edge of the first step and ending in the middle at the step in level with the platform. The width of the stair is set to a constant value of 1.25 metres. The grid for the stair is set to 0.625 metres, giving that two people can walk next to each other on the stair. Compared to the grid in the train this is corresponding very well to the train dimensions.

Since every person occupies one grid cell, the grid cells are used to mark the initial positions for each person in the train. Passenger can either be seated or standing which gives two initial positions. The passenger-sitting position is created in STEPS by adding a delay to the person before moving, this delay is chosen to be 2.5 second, an empirical value. The position of people is at every of the permanent seats, in the corridor between the seats, and the corridor leading out to the door. This is shown in figure A.4, where every grid cell from which a person starts is marked.

To make a precise location for each person in the train a cell of 0.5x0.5 m^2 for each of the 46 start positions are defined. Each cell needs to have at least one exit, an open boundary. It is chosen to be at least one of the sides of the cells, pointing towards the direction that the person naturally would walk in.

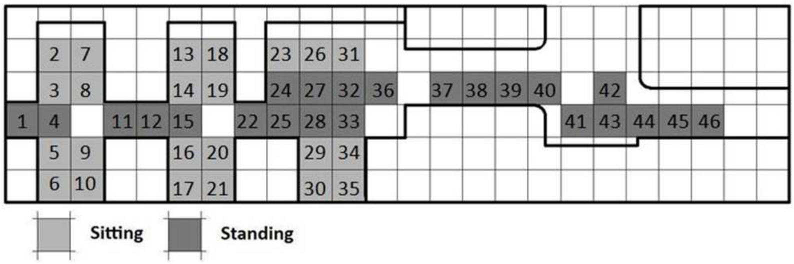

Figure A.4: Placement of persons inside the train

Setups

Two setups are investigated and simulated in STEPS; the first accounts for able-bodied people only, the second involves a mixed population comprehending for age distribution as well as impairments such as hearing, visual and mobility. The composition of the mixed population corresponds to the demography of Denmark.

Six different groups are defined on the base of only one parameter and the gender is not considered for any of the groups. The six groups are characterised as follows

- Able-bodied people (young healthy people) (Std.)
- Children (C)
- People with a cognitive disability, (Co)
- Elderly, (E)
- Hearing disabled people (H)
- Visual disabled (V)

The composition of the two setups investigated is shown in Table A.1. In STEPS it is possible to set the colour of the person types; skin, jumper, shoes, pants, and hair. This option is used for recognition of the different groups in the model, when the simulation is ongoing. An illustration of the person types are shown in figure A.5.

People type velocities

Table A.1: Distribution of people in the different setups

Characteristics	Setup	
	1	2
Able-bodied	46	23
Children	-	8
Cognitive	-	2
Elderly	-	8
Hearing	-	3
Visual	-	2

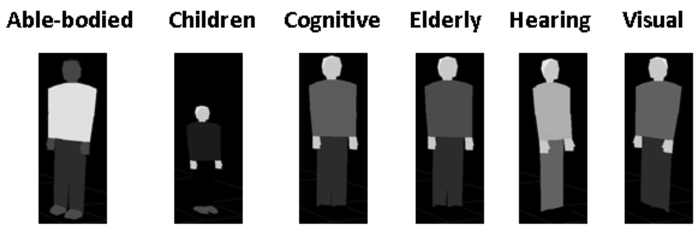

Figure A.5: Appearance of each group in STEPS

Six different groups of persons are created in STEPS. Since the current simulation is set to have one person per grid cell the dimensions of people in the different groups, does not have an influence on the flow. Because of this the dimensions of the different people types are the same, except for the children, who are 1.2 meters high and are 0.36 meters in width and 0.22 meters in depth, which is approximately 75% of the adult dimensions. This affects the person density. Table A.2 gives the walking speed for each of the six groups together with the time delay from the start of the simulation until persons in the particular group starts to move. The difference in the delay times for the standing situation is based on the assumption that not everybody reacts simultaneous. The range of five seconds between the six different groups is chosen because people are placed relatively close to each other and the reaction of the first person will affect the rest and they will start moving as well.

Table A.2: Maximum walking speeds and delay for each group

Characteristic	Walking speed [m/s]	Delay in STEPS [s]	
		Standing	Sitting
Able-bodied	1.13[a]	0.0	2.5
Children	0.84[b]	3.0	5.5
Cognitive	0.75	3.0	5.5
Elderly	0.55	2.5	5.0
Hearing	1.06	4.0	6.5
Visual	0.98[c]	5.0	7.5

[a] (Sørensen L. S., 2004)
[b] (Larusdottir & Dederichs, 2010)
[c] (Sørensen J. G., 2011)

The delay assigned to the sitting situation is the delay from a standing position added 2.5 seconds. This is an estimate on how long time is needed before the sitting people rise and are ready to begin their evacuation.

The velocities for the able-bodied, children and people with visible impairments are taken from real data experiments, while the velocities for the elderly people, people with mobility impairments and audio impairments were set, since no data is available for these groups. The data for children and the able- bodied are used as a reference when setting these values.

The velocity of the able-bodied is given by the data from (Sørensen L. S., 2004) The velocities of children and people with visual impairments are taken from real data (Larusdottir, 2009) (Sørensen J. G., 2011). The estimated velocities for the cognitive population are set to be slightly lower than the walking speed of children with $v = 0.75m/s$. Elderly persons are assumed to be the group with the lowest walking speed of 0.55 m/s. This is based on a consideration that the aging process affects locomotion. For the population of hearing impairments the mean of the able-bodied and the visual impaired are used. The assumption is that a person with hearing disabilities is slower than an able-bodied person and faster than a person with visual disabilities. As STEPS take the density into account in the simulation it is chosen to use the 'Use Speed/Density Curve' from the SFPE Handbook. This is done for every person type. STEPS does not account for social affiliation, hence, people are not waiting for each other in the simulations.

Results and discussion

The evacuation simulation tool STEPS is used to model the evacuation from a train in a tunnel, a process very similar to the evacuation from a train on a bridge. STEPS was randomly set and the passengers do not exit doors and descend stairs in the same order every time. This randomization gives different results from run to run. In order to obtain a valid sequence of runs for the analysis each setup is simulated 50 times, and the average total evacuation time is determined. The results for the two setups are given in figure A.6.

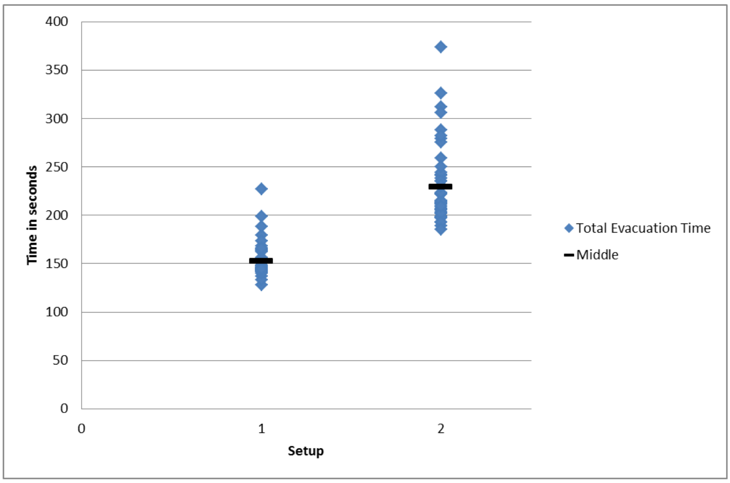

Figure A.6: Total evacuation time and average time for each of the four setups

A comparison between the two setups based on the fastest, the average and the slowest total evacuation time shows that the homogeneous setup containing able-bodied people, for all three measures, are faster than for the mixed test population. Table A.3 displays the exact times in seconds derived from the two setups. This indicates that a mixed population will have a larger total evacuation time. The model is based on the assumption that the walking speed drops,

Table A.3: Evacuation time in seconds for the four setups

	Setup 1	Setup 2
Fastest [s]	128	185
Average [s]	152	229
Slowest [s]	227	374

with increasing surrounding density. The simulations indicate that a person's density is not only dependent on the density in front of him/her, but also next to and behind the particular person. This observation does not correspond to the expectations from everyday life observations, and an experiment in real life would therefore probably give slightly faster total evacuation times.

The first setup, solid black line in figure A.7, gives the fastest evacuation time. The total evacuation time, for the first setup, comprising only able-bodied people, gives a total evacuation time of 152 seconds. The time of exit for each person is shown in figure A.7.

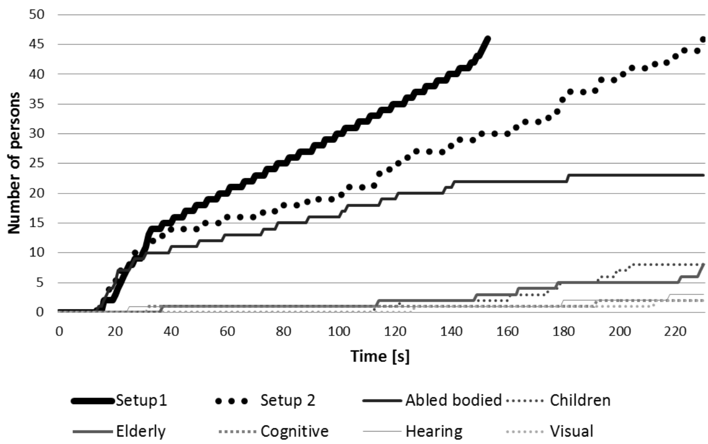

Figure A.7: Exit times for setup 1 (solely able-bodied population) and 2 (heterogeneous population)

It is seen from figure A.7 that the first person has reached the safe place after 16 seconds, until 33 seconds the number of people in safety increases rapidly ending at 14 people. From this moment, the person flow is considered linear until all passengers have reached a safe place after 152 seconds. The change in the curve at 33 seconds is due to the fact that people in the brougham need to negotiate the door and this creates a bottleneck. The most used evacuation theory gives that an increase in density results in decrease in walking speed. Opposite when the density decreases the walking speed increases. This is one explanation of the linearity of the curve, since the critical passage of the evacuation path is the door from the brougham implies an increase in density. The small increase at the last seconds is because the density is low when the last two persons exits the brougham, and thereby can do it very close to each other.

The second setup is shown in the remaining lines in figure A.7. It is more complex than the first setup. Six subgroups of people are represented in this setup: 8 children, 8 elderly, 2 visual, 3 hearing, 2 cognitive and 23 able-bodied people. The data from the setup is plotted the same way as setup one. The total number of evacuated due to respect of time is shown and the same is applicable for each of the six groups of people. The total evacuation time is 229 seconds, which is an increase of more than a 50% compared to the setup with only able-bodied people.

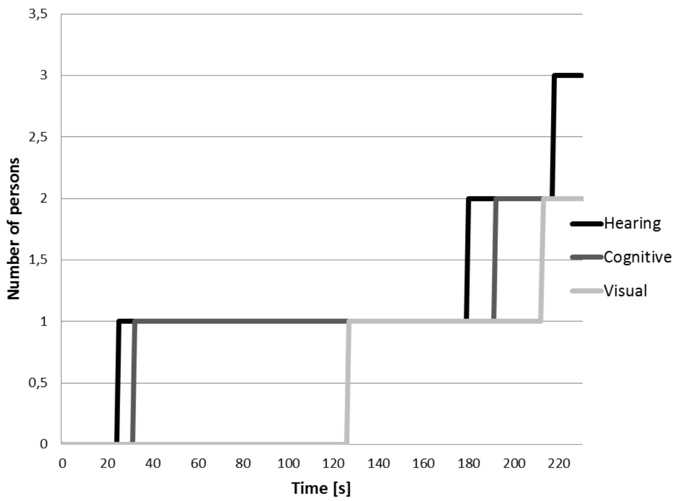

Figure A.8: Exit times for setup 2 (heterogeneous population)

The time before anyone exits the tunnel, is the same as for setup 1, and there is a rapid increase before the curve for the total evacuated more or less becomes linear until everybody have reached the place of safety. It can be seen that for the first 112 seconds only three people besides able-bodied people have reached the place of safety. This is due to the initial placements of people, where only three people not considered as able-bodied people are placed in the corridor of the train. The three passengers are; one hearing impaired, one with a cognitive disability and one elderly person. These three are also the first non able-bodied people out of the train after respectively 25, 32 and 37 seconds.

In this setup the door from the brougham to the corridor likewise creates a bottleneck, the groups with lower walking speeds than able-bodied people is assumed to negotiate the door slower, and thereby the time for everybody to get out of the train increases. The homogeneous group of able-bodied people is faster than the other groups, and can overtake them at the platform and cross tunnel. This can be seen since the last able-bodied person exits approximately 40 seconds before the last person have reached the place of safety.

This setup indicates that it is necessary to further investigate the evacuation times for mixed populations, and especially for people with disabilities.

Figure A.8 shows an extract of figure A.7, presentation of the evacuation times of the impaired subgroups. In the simulations the total evacuation times of the hearing impaired is 183 seconds, the cognitive impaired is 198 seconds and the visual impaired is 213. These times strongly depend on the assumptions of the velocities for two of the groups (the hearing and the cognitive impaired). More real data would be needed to describe these groups. This data is essential as input for the model as well for validation purposes.

Conclusion

The evacuation of trains on bridges is a considerable scenario of evacuation. The problem is comparable to the evacuation from trains in tunnels, except for the possible confinement of the smoke in tunnel. Evacuation characteristics of homogeneous populations are frequently used in the design phase of complex buildings. The present study is on comparing the evacuation times of homogeneous and mixed populations from a train in a tunnel using the model STEPS. The passengers were set to randomly exit doors and descend stairs during the different simulations. Two setups were compared: one describing a homogeneous population consisting of able-bodied people only and a second accounting for a variety in age and impairment comprehending elderly people, children, and people with hearing, cognitive and visual impairments. The model was run 50 times. The study gave the following findings:

The homogeneous population of able-bodied people was faster than the mixed test population. The average evacuation times of the mixed populations were 40% slower, than the evacuation times of the homogeneous population of able-bodied people. The initial placement and seating of the people in the train affect the evacuation times. More real data on subgroups of a mixed population are needed as input and validation data for models like STEPS. For the impaired group the total evacuation time for the hearing impaired is 183 seconds, for the cognitive impaired is 198 seconds and for the visual impaired is 213 seconds. This comparison of the impaired subgroups is limited by the fact that there is only input data for the visual impaired group and the input of the hearing and cognitive impaired populations is based on assumptions of the velocities. More real data is needed to describe these groups. This data is essential as input for the model as well for validation purposes.

Aknowledgement

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Appendix B

Evacuation characteristics of Blind and Visually Impaired People: Walking speeds on horizontal planes and descending stairs

Type	Conference Paper
Title:	**Evacuation characteristics of Blind and Visually Impaired People:**
	Walking speeds on horizontal planes and descending stairs
Author:	J.G. Sørensen and A.S. Dederichs
Conference:	5^{th} International Symposium Human Behaviour in Fire
Date:	September 19-21, 2012
Location:	Cambridge, UK

Abstract

Sustainable building design comprises also fire safety design. Social quality is one factor for the determination of the sustainability of building design. With respect to fire safety design this may imply equal egressibility for every person in buildings in case of emergency, irrespective his or her age, or whether they carry an impairment or not. However, the large group of people with impairments is still poorly described. The goal with the current study is to gain data on people with visual impairments, as only a few studies are carried out on this population. 18 evacuation experiments involving the homogeneous group of visually impaired people have been carried out. Walking speeds and total egress times have been measured. The study has the following findings: The walking speed horizontally at low densities is significantly lower for people with visual impairments compared to able-bodied people. This is also the case for increasing person density. However, the trend is comparable with the theory for able-bodied people. Concerning stairs the walking speed at low densities is in the same range as the values provided in Scandinavian guidelines, but is lower comparing with the theory of Nelson and Mowrer and experiments on able-bodied people. While the density increases the results for the walking speed descending stairs shows that people with visual impairments only are affected to a limited extend.

Introduction

The demand on more flexible building design is increasing. Nevertheless, fire safety design of buildings is primarily based on the prescriptive codes, which are set after sequences of real fires [1]. Prescriptive codes give requirements on e.g. maximum distance to nearest exit, width of exits and number of exits etc. These requirements limit the architectural freedom and lead to the establishment of traditional buildings, divided into sections and subsections. Sectioning of the buildings shall enable confinement of fire and smoke. Nowadays designers have difficulties fulfilling the requirements in the prescriptive codes due to a demand on innovative design and an increasing number of complex buildings [2]. Hence, performance-based codes for fire safety design were implemented in building regulations worldwide, during the last twenty years [3,4]. The codes allow innovative design, as long as the safety of the building can be verified. The safety level can be established applying fire safety engineering methods to determine RSET (Required Safe Egress Time) and ASET (Available Safe Egress Time). Most numerical and hand calculation methods for the determination of the ASET are developed on the basis of studies on able-bodied people. This population is chosen, because of its homogeneity and maybe because of its availability; students of universities or members of the military. This choice is made even though the population involved in real fires also contains children, elderly people and people with disabilities in a considerable number of individuals [5].

Studies have shown that the vulnerable part of the population is more likely to suffer in case of fire or other emergency situations [6]. Furthermore, the increasing focus on accessibility to buildings leads to an increased physical presence of people with disabilities in buildings. However, the accessibility is not an assurance for egressibility[7]. It is therefore important to consider this part of the population in the fire safety design.

Another aspect is the demand on sustainable building design, where social quality is one factor used for the assessment of a design[8]. Considering all users of a building and giving them equal possibilities to apply the functionality of the building contributes to the social quality of the design. In the context of fire safety design one goal should be to enable egressibility and avoiding a design where parts of the population need to be rescued by the rescue service in a later stage of the fire development.

In order to fulfil such requirements the needs of all parts of the population have to be qualitatively and quantitatively described. Evacuation characteristics of the heterogeneous population need to be investigated, comprehending age and impairments. The population in focus of the current study are people with visual impairments. 285 million people worldwide have reduced sight. Hereof 39 million are blind and 246 million have a decreased visibility [9]. Some individuals in this population are blind by birth or accident; others gain the impairment with age. Studies have shown that 79% of all 55 year old people are in the need of glasses for sight correction [10]. The evacuation process is affected by the ability to use vision for orientation in emergency routes, locate exits and exit signs. When a fire alarm sounds and an evacuation starts people without visual or hearing impairments use their sight, in order to read the reaction of the surrounding people, locate exit signs or exits [11]. This part of the population processes information using their eyesight. Additionally people without visual impairments, react on queues and smoke during evacuation. Blind and visually impaired people need other types of information during an evacuation situation in order to process the relevant information.

Little information on prevalence, type and mobility of disabled people as well as walking speeds horizontally and on inclined planes can be found in litterature [12,13]. However, studies are limited and results for blind and visually impaired people are very sparse. The focus of the present study is thus on the evacuation capability of blind and visually impaired people and investigates the walking speeds on horizontal planes and descending stairs and their interactions with the environment.

Method

The present study is an experimental study focusing on walking speeds horizontally and descending stairs for a homogeneous group of blind and visually impaired people. Evacuation exercises were carried out in four different buildings located different places around Zealand, Denmark. Corridors and stairs were a part of the means of egress in all four buildings. Two buildings had two storeys and two buildings had three storeys. Three different types of evacuation exercises were carried out:

- evacuation of single persons,
- evacuation of groups,
- unannounced full scale exercises.

All 46 participants had with a visual impairment with different degree of vision loss, gender and age. The population consisted of 30 males and 16 females aged between 10 years and 69 years. The experiments were carried out in the period from February to May 2011. The results presented in the following do not address the specific differences in the degree of vision loss and the visual categories will therefore not be explicitly presented.

Data was collected using temporarily fixed video cameras. The cameras filmed from directly above to measure person densities and turning and angle to observe interactions between participants and environment. On horizontal planes the density was measured on a reference area of 2 m^2 corresponding to an area of 1 meter in front and behind the particular studied person. The width of the reference area was 1 meter with the particular person centred, see figure B.1. The advantage of this method is that the local density registered by the person is more realistic than considering a global density from a larger area. In addition, too low densities compared to a real situation are avoided. When imagining a large group of people walking together in a long corridor, the global density calculated using the whole area of the corridor should be lower, compared to the local density experienced by the people in the bulk. The density calculated on the basis of the 2 m^2 is assumed to give a more representative local density around the studied person. The disadvantage of this method is that densities below 0.5 m^2 cannot occur, because the person load within the area always is at least one person. Furthermore, people walking with a guiding dog accumulate a higher density, because the dog is counted as a person, as it influences the walking speed. There have been several discussions on how to define the area where the density is measured [14,15,16]. Another approach is to calculate the density within a bulk. Applying this method requires clear definitions, on what can be categorized as a bulk, comprising the internal distance between people, the relation between people, and the number of people walking together. This method has a higher work load, than the applied method using the 2 m^2 area.

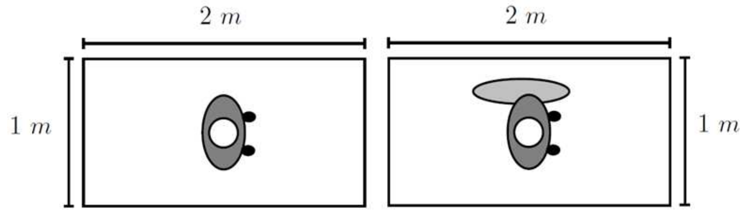

Figure B.1: Definition of reference area used for density calculations for single persons and persons having a guiding dog.

Density measurements on stairs are different from horizontal planes. For a stair there are two ways to measure the density dependent on the design of the stair. If the stair between two floors is a straight stair flight, the density is measured in two parts, where the stair is split equally, vertically. If it is a two flight stair with an intermediate landing, the density is measured on each stair flight. Using this method error, regarding the distribution of people on the stair, can be minimized. If a stair between two floors contains more than two flights, the density is measured on every flight.

Ethics

This study involves human beings and investigates their characteristics and behaviour during an evacuation situation. When human beings are a part of a scientific project the ethical aspect needs to be considered. In order to ensure that all participants were well informed about the exercises all participants received oral and written information about the evacuation exercise beforehand. In addition each participant signed an informed consent to permit filming during the exercise. The participants were guaranteed anonymity and were informed that the exercises were held on a voluntary base.

In many countries experiments comprising human beings need to be approved by various ethical committees [17,18]. However, in Denmark scientific projects comprising human beings shall as a rule be notified and approved by the National Committee on Health Research Ethics. In case the project is categorized as a registration research project, which does not involve any biological material from participants, the ethical committee does not need to be notified. In addition the participants are not exposed to any extraordinary conditions because the exercises are held in their natural environment[19].

Besides the National Committee on Health Research Ethics, the Danish Data Protection Agency should approve scientific projects if personal information is treated. This agency enforces the act of personal data. The project was approved by this Danish Data Protection Agency, since personal health-related matters can be identified on the videos.

Results

The results obtained during the experiments and discussions of these are presented in the following section. The walking speeds horizontally and descending stairs are separated into 2 parts;

- the free walking speed,
- density dependency of the velocities.

Participants are considered to walk unimpeded and at their own walking path for person densities less than 0.54 $pers/m^2$ which is used as the limit for the free walking speed. The results are compared to the theory of Nelson and Mowrer [20], the commonly used theory in today's fire safety design. All the presented results are based on a homogeneous population of blind and visually impaired people. No distinctions are made in the degree of visual loss. However, a tendency among the results shows that there is a difference in walking speeds depending on the degree of visual loss.

Walking Speeds horizontally

The results obtained from the experiments give a mean free walking speed of 0.98 m/s on horizontal planes. However, the walking speed varies between a minimum speed of 0.35 m/s up to a maximum speed of 1.72 m/s. The free walking speed horizontally found in literature and national codes ranges from 1.19 m/s up to 1.34 m/s. Comparing the free walking speed from the experiment and the literature or national codes shows a significant difference, which implies that the lowest theoretical value is around 20 percent larger for able-bodied people compared to blind and visually impaired people.

For able-bodied people the walking speed decreases as the person density increases, it is therefore investigated if this trend is the same for blind and visually impaired people. In the exercises the highest density found is 2.24 $pers/m^2$ corresponding to a medium density, where low densities is defined as densities below 0.54 $pers/m^2$ whereas high densities occurs when the density exceeds 3 $pers/m^2$.

The relation between the walking speed and the person density obtained from the experiment are given in figure B.2 together with the theory of Nelson and Mowrer for able-bodied people.

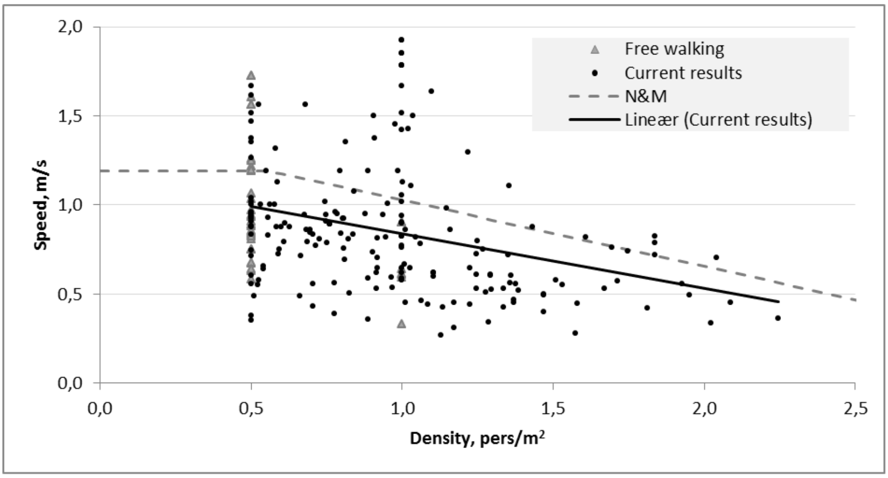

Figure B.2: Relation between walking speed horizontally and density.

A high concentration of data points can be seen for densities equal to 0.5 $pers/m^2$ and 1.0 $pers/m^2$. The reason for this is the method applied for density calculations. The setup of the exercises has induced many results for these two values because different groups of different size are studied. The data points with densities equal to 0.5 $pers/m^2$ are measured, when the participants are walking with a distance larger than one meter to other participants. The amount of data points for densities equal to 1.0 $pers/m^2$ are measured, when participants with a guiding dog are walking with an internal distance larger than one meter to other participants.

The trend line for the experiments is formed as the best linear fit from the results. The choice of a linear function is due to the applied theory by Nelson and Mowrer. The theoretical relation is described as a linear function, for densities higher than 0.54 $pers/m^2$, and is given by

$$v_{theory} = -0.372D + 1.4 \tag{B.1}$$

whereas the equation for the trend line obtained in the experiment is given by

$$v_{experiment} = -0.309D + 1.15 \tag{B.2}$$

Comparison of the two trend lines, equation B.1 and B.2, shows that the mean walking speed for all blind and visually impaired people are lower than the value for able-bodied people. The trend line is displaced downwards, but the slope is quite similar to the theoretical value, however less steep. If this trend remains the same for higher densities, the two lines will cross each other. This indicates that for increasing densities, blind or visually impaired people are able to maintain a higher walking speed, compared to able-bodied people without visual impairments. The deviation among the results may be explained by individual factors such as age, gender and physical conditions, but could likewise be addressed by the method applied for the density calculation. If the area, where the density was measured, was re-fined into smaller areas, the deviation might be decreased according to Steffen and Seyfried 201016.

Another observation illustrated in figure 2 is that some of the participants are able to walk without any influence of their vision loss or impairment, because they have the same or higher walking speed as able-bodied people without vision loss (data points above the theoretical curve). The reason for this can be that all exercises were carried out in the participant's natural environment, and the knowledge of the building can be categorized as very good.

On the base of the results it must be concluded, that the theory applied by Nelson and Mowrer, is not conservative for blind and visually impaired people. It is therefore not conservative to use this theory, when this group of people is considered.

Walking Speeds descending stairs

Travelling on stairs people are able to walk with their own free walking speed at densities less than 0.54 $pers/m^2$. The current experiments give an average free walking speed descending stairs on 0.73 m/s. The maximum walking speed is measured to 0.92 m/s whereas the minimum is 0.54 m/s. The standard deviation in these experiments is 0.09 m/s. The values are presented in Table C.1, where the theoretical value for able-bodied people given by Nelson and Mowrer (N&M) and values from different national codes are presented for comparison. The value from the national code in the US depends on the design of the stair and an interval for different stairs are displayed. All values not from the experiments are assumed for able-bodied people.

Table B.1: Free walking speed descending stairs for the experiment, theory by Nelson and Mowrer (N&M) and national codes

	Experiment	N&M	Denmark	Sweden	US
Mean $[m/s]$	0.73	1.01	0.7	0.75	0.85-1.05

The free walking speed descending stairs is in the same range as the value given in Scandinavian national codes whereas it is smaller in comparison with the theory of Nelson and Mowrer and the US guideline. The table shows a variation within the suggested walking speed descending stairs in different countries. However, it seems like the free walking speed descending stairs cannot be evaluated as dependent on the vision loss for the Scandinavian countries. This might be explained by the knowledge of the building and the stairs. In all the exercises the participants were very familiar with the stairs and used them on a daily basis. Another aspect is the geometry of the stairs. All stairs were equipped with handrails which is an essential tool in orientation for blind and visually impaired people. Likewise the stairs often is less wide compared to a corridor which might give the blind or visually impaired a feeling of safety.

The theory for able-bodied people of Nelson and Mowrer gives that the walking speed descending stairs in addition is dependent on an increasing density as the case with the walking speed horizontally. The relation between the walking speed descending stairs and the density is given in figure B.3 for this experiment.

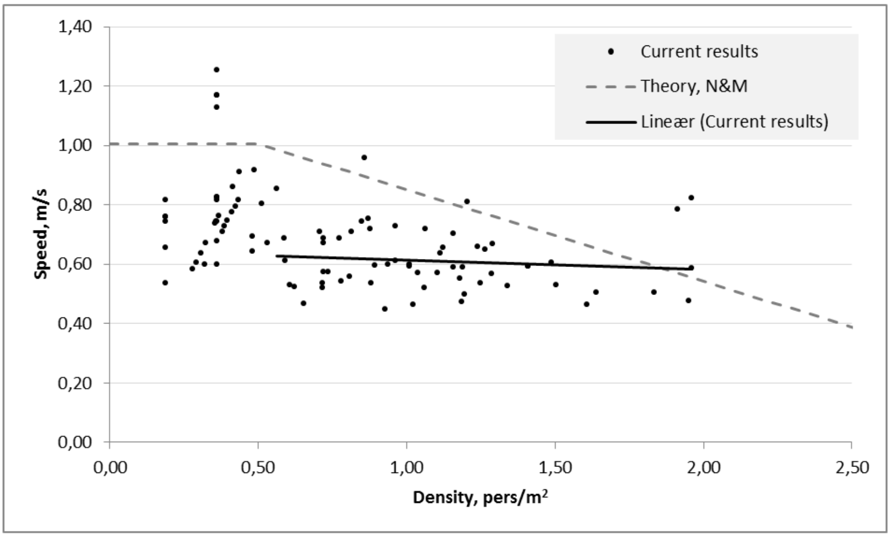

Figure B.3: Relation between walking speed descending stairs and density.

The theoretical relation for able-bodied people (dotted line) between the walking speed descending stairs and the density for an average stair corresponding to the ones used in the experiments is given by

$$v_{theory-stair} = -0.285D + 1.071 \tag{B.3}$$

Whereas the equation for the trend line obtained from the experiments for visually impaired people is given by

$$v_{experiment-stair} = -0.032D + 0.647 \tag{B.4}$$

Equation B.3 and B.4 describes the speed density relation for able-bodied people and the experiment on visual impairments. The difference between the two equations is evident. The trend for the theory by Nelson and Mowrer is that the speed decreases linearly as the density increases. This is however not the case for the current results. Here it is seen that the speed is almost constant even though the density increases as a result of the very small value for the slope. The result indicates that blind or visually impaired people are able to maintain the same walking speed descending stairs even though the density increases. This tendency might be explained by the fact that this group will not be able to determine the amount of people around them visually.

On the base of the results obtained it must be concluded, that the degree of visual impairment matters while looking at the walking speed descending stairs. The trends for blind or visually impaired people are very different compared to the theory for able-bodied people applied by Nelson and Mowrer. It seems like the walking speed is kept constant even though the density increases.

All the exercises were carried out in the participant's natural environment, which might have affected the results, because they were familiar with the surroundings, and were used to travel along corridors and on stairs on a daily basis. Additionally interviews on the evacuation experience were carried out after the exercises. One of the questions was "Was it important for you that you knew the surroundings well?". All participants answered "Yes" and half of them added that it had a large effect. One comment was "Yes, of course it was absolutely critical, yeah almost of fatal crucial importance" (translated from Danish). A decrease of the walking speed on horizontal planes and descending stairs can be expected if the exercises were carried out in unfamiliar environments. The reason why the natural environment was chosen was to decrease uncertainties among the participants and encourage them to act "normal".

People differ from each other and the individual factor therefore influences the results. There are differences in age and gender, but also the mobility capability of the participants, some people are able to walk without any types of aid and some need a cane, a guiding dog or physical assistance from a non-visually impaired person. Performing exercises comprising human beings always have natural fluctuations, because human behaviour cannot be predicted, and this therefore has to be considered in the analysis of the results. All human factors are reflected in the results. Concerning fire safety design, this factor need to be considered because it also appears in a real emergency situation.

Human behaviour and interactions observed

During the exercises the behaviour of the participants was observed. The most common observation was that the walls were used as guiding lines. The participants used their hand and fingers on the walls, to feel where they were. It was observed, that the touching was light, and it seems that the fingers were dancing on the wall. The participants preferable walked near the wall on their right hand side. Another observation, which was common for all the exercises, where stairs were used, was that the handrails were used for orientation. If the width of the stairs allowed for it, handrails in both sides or the handrail and the wall were used for orientation, while the participants were travelling on the stair.

It was observed, that the participants walking alone slowed down their speed, when they noticed an obstacle in their way. They were relatively close to the obstacle when they registered it, and were slowing down, in order to figure out how to pass it. People without vision loss would have been able to adjust their walking path in order to avoid obstacles. However, this is not an option for blind and visually impaired people. It is therefore of great importance to keep the egress routes free of obstacles, because obstacles can result in an increase of the evacuation time for this group of people. Furthermore, the general capacity of the egress route is lowered, if obstacles are in the way.

While the egress route includes wide corridors the participants were walking by the wall, in order to use it as a guiding line. It increased their ability to travel safe and determine where they were. Likewise the walking speed is assumed to be higher, because they were more secure and might feel more comfortable with the situation. In the buildings used for the exercise, the participant's used specific marks placed on the walls, for orientation through the egress routes.

While the participants were walking in groups it was a common observation that they were waiting and felt responsible for each other. It is assumed that this is caused by the instructions on how to perform the exercises, but also due to a strong personal relation between the participants as they knew each other beforehand. If this has not been the case, there might have been a personal relation anyway because they share the same difficulties, and thereby know about each other's situation. Another aspect, that strengthens this relationship is, that the ones with best vision were assisting the ones with a more poor vision during the exercises. The assistance consisted of e.g. holding doors for one another and verbal communication. Furthermore, some participants were going back to help those who were lacking behind. This affiliation could cause dangerous situations in a real emergency situation. Both persons could therefore be trapped in the building and it is better to leave the rescue part for the professional fire fighters.

During the full scale exercises it was observed, that the participants quite quickly were walking towards the decided assembly point inside the buildings as they heard the fire alarm. Here they were waiting for instructions from the non-visually impaired assistants. The participants carefully followed the instructions from the assistants, and they were walking in a line and stayed together during the exercise.

In some cases it was observed that the blind or visually impaired participants were holding their ears due to a very noisy alarm signal. This behaviour could cause dangerous situations, as the participants could fall. They can be injured and might not be able to continue the evacuation. However, blind and visually impaired people do not have a better hearing, compared to able-bodied people without vision loss, but have sharpened senses, if the sense is trained [21]. Additionally, bad behaviour from able-bodied people was adopted by the blind or visually impaired people, because they were forced to follow the assistant. An example observed was a running non-visually impaired assistant holding a blind or visually impaired participants hand during the exercise.

Conclusion

The current study gives new information and data on the evacuation characteristics of blind and visually impaired people. The study shows that the evacuation capability of blind and visually impaired people is different compared to able-bodied people.

The investigations for walking speeds horizontally at low densities show that blind and visually impaired people have a lower free walking speed compared to able-bodied people according to the theory of Nelson and Mowrer. The walking speed for blind and visually impaired people is 0.98 m/s and in comparison it is between 1.19-1.34 m/s for able-bodied people. While the person density increases it was observed that the walking speed horizontally decreases linearly as for able-bodied people. However, the point of origin is lower than for able-bodied people. On the basis of this it is showed that the form of the curve for walking horizontally shows the same tendency as for able-bodied people. Hence, the curve is displaced downwards and gives a considerable lower walking speed which might affect the evacuation flow depending on the design of the egress path. The main conclusion for the walking speed horizontally is that it is not conservative to apply the theory for able-bodied people suggested by Nelson and Mowrer on horizontal planes for blind and visually impaired people.

Considering the stairs it can be concluded that the free walking speed for blind and visually impaired people are comparable with values provided in Scandinavian guidelines whereas the theoretical value of Nelson and Mowrer and US guideline provides higher walking speeds descending stairs. This implies that the theory by Nelson and Mowrer is not conservative for the population of visual impaired people. For an increasing person density the study shows that the walking speed decreases. However, the slope of the trend line is not comparable with the slope for able-bodied people. The slope for blind and visually impaired people is less steep and almost constant compared to the able-bodied people. It seems like the influence of an increasing density on the walking speed descending stairs is very limited and more data is needed.

Regarding the human behaviour during the exercises it is seen that blind and visually impaired people use walls and handrails in general, when they orientate in a building. All kind of obstacles can cause problems for blind and visual impaired people. They are not able to register these on a long distance, and thereby adjust the speed and walking path. Consequently, it is of importance to keep all egress routes free from obstacles. Additional a large responsibility for each other is observed and the one with the best vision assists the ones with a more poor vision.

The investigations carried out throughout this study shows that people with visual impairments cannot be treated as able-bodied people. This part of the population has its own evacuation characteristics and special needs during an evacuation. It is therefore of importance to be aware of this while calculating total egress times. Additionally this study contributes to the sustainable building design by enabling fire safety engineers to improve the egressibility of the visually impaired population.

Acknowledgement

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Appendix C

Evacuation from a complex structure - The effect of neglecting heterogeneous populations

Type	Conference Paper
Title:	**Evacuation from a complex structure**
	The effect of neglecting heterogeneous populations
Author:	J.G. Sørensen and A.S. Dederichs
Conference:	The Conference on Pedestrian and Evacuation Dynamics 2014 (PED2014)
Date:	October 22-24, 2013
Location:	Delft, Netherlands

Abstract

How is the total evacuation time of a mixed population and its subgroups predicted by the evacuation tool STEPS? Simulation using STEPS is compared with experimental data and evaluated based on individual total egress times. It was found that the total egress times were similar for the simulation and experiment, but the human behavior occurring in the experiment was not reproduced in the simulations.

Introduction

Societies increasing demand for complex buildings and structures requires more flexible building design in general as well as a flexible fire safety design. Performance based fire safety codes provide solutions for an adaptable design. Hence, these codes are increasingly implemented around the world as a supplement to the existing prescrip-tive codes. The use of performance-based codes enables the use of tools, such as computer models, to proof that the safety level in the current building is sufficient. The focus of the current study is common evacuation models, in particular STEPS, and the need for valid input data (e.g. walking speeds and delay times for a realistic population) to predict representative and realistic evacuation times. The majority of studies on walking speeds and delay times from literature evaluates the evacuation behaviour of homogeneous groups, often able-bodied adults, and applies normative standards for the choice of population (Gwynne, et al., 2005), (Boyce, et al., 1999a). It appears that the safety level in buildings is not the same for individuals of vulnerable part of the population, as for able-bodied individuals. Research has shown that people with physical and cognitive disabilities, individuals aged younger than 5 years or older than 64 years as well as people impaired by drugs, are more likely to die in fires, compared to able-bodied individuals (Marshall, et al., 1998), (Leth, 1998). This makes it of high concern to focus on the fire safety provided in buildings for this group of people.

Literature Review

A series of studies describing the evacuation processes from buildings and vehicles (ITSRR, 2004), (Gwynne, et al., 2003), (Tubbs, 2009), (Kuligowski, 2009), (Grindrod, et al., 2011) have been undertaken. The evacuation of high-speed trains has been studied by Capote et al. (Capote, et al., 2012). It has been shown, that the effect of the action of the train crew was more important for a smooth and fast egress, than the self-preservation of the passengers. Furthermore, it was found that the flow predicted using the empirical model by Nelson and Mowrer, (Nelson & Mowrer, 2002), was conservative compared to the average of the data found in the experiment. The study also involved wheel chair users, and it was concluded that the need of assistance by the crew was essential for the evacuation of this subpopulation. The evacuation flow was likewise studied by Galea et al. for an overturned rail carriage (Galea & Gwynne, 2000). Here it was shown that presence of smoke almost doubled the total evacuation time from the overturned rail carriage. In a study conducted by Oswald et al. the floor height in trains was investigated to clarify how the evacuation flow and behaviour were affected, (Oswald, et al., 2010). There are several other studies on the evacuation from airplanes and boats (Gwynne, et al., 2003), (Galea, et al., 2004), where the evacuation efficiency has been shown to increase with number of cabin crew (Galea, et al., 2008).

A number of models describing the evacuation process can be found in literature (Kuligowski, et al., 2010). Some of the assessed models are not validated, while others are validated using different methods; see Table 1 in (Kuligowski, et al., 2010) for details. The methods range from comparison with full-scale fire drills to other people movement experiments (Kuligowski, et al., 2010). Furthermore, literature on past evacuation experiments, code requirements, validation against other models or third party validation are used in the validation process (Kuligowski, et al., 2010). The method of validation helps defining the limitations of the applicability of the model. Studies have found that age, gender, time of day (Weidmann, 1993), as well as interpersonal distances and densities (Dabbs & Stokes, 1975) affect the average walking speeds during an evacuation. Furthermore, it has been shown that some modelling approaches are based on "inaccurate assumptions about the way humans respond during emergencies", which may lead to the production of inaccurate results according to Kuligowski, (Kuligowski, 2011).

Kuligowski et al. reviewed 26 egress models and found that 21 allow a description of the evacuation capabilities of disabled people (Kuligowski, et al., 2010). There are different ways of accounting for the heterogeneity of a real population and including disabled people in the building environment. Campanella et al. (Campanella, et al., 2009) showed that an increasing heterogeneity in the population affects average speeds, densities and more likely lead to break down of the flow.

Objectives

The current work centre on the evacuation modelling tool STEPS, which allows the description of people with impairments in the evacuation process. STEPS is chosen among other modelling tools. STEPS is a behavioural model, which means it is capable of modelling occupants performing actions and their movement towards a speci-fied goal. The setup of these experiments and the hypothesis to test is whether the model is able to predict the behavioural patterns of each of the subgroups. This specific model is validated according to code requirements, fire drills and other people movement experiments as well as literature on past experiments (Kuligowski, et al., 2010). However, it is known that there exists limited information and literature on the evacuation capabilities of people with disabilities, (Boyce, et al., 1999b).

Details on the evacuation experiment and the evacuation model build up in STEPS are explained in the following section. Results on total evacuation times for the real exercises and for the simulations, differentiated for the six subpopulations: mobility-, visual-, auditory-, and cognitive impaired people as well as able-bodied people are presented. In the conclusion the main highlights of the current work is presented.

Full Scale Experiment

The study contains two parts: an experimental part, where full-scale evacuation exercises are performed from a train in a tunnel and a comparative study between the experiment and simulations of the same experiment.

Firstly, the method applied for the setup of the experiments is presented. Secondly, it is described how the associated evacuation calculations are performed using the program STEPS 5.1. The average unimpeded walking speeds are found for each subpopulation in the experiment, and are added into STEPS 5.1 together with measured delay times to start moving. This is done in order to perform simulations of the experiment that uses exact values from the experiment combined with default options.

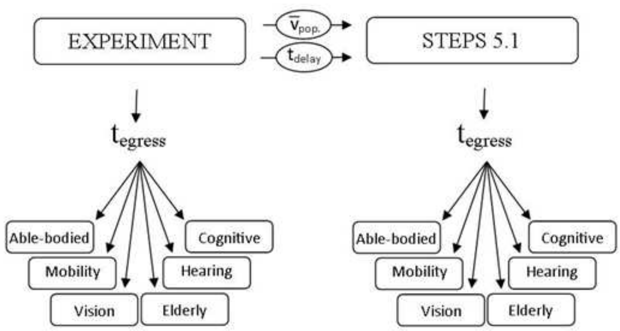

Figure C.1: Relation between the experiment and simulations

The linkage between the experiment and the simulations performed with STEPS is displayed in Fig. C.1. The mean velocities for each subpopulation, obtained for the unimpeded walking in the experiment serves as input to the STEPS model. In addition the delay time to start moving is measured in the experiments and is also an input parameter to the model. Two different evacuation times, t_{egress}, is obtained. These evacuation times will then be decomposed to a representation of the individual egress times for each member of the subpopulations. The evacuation experiment is performed from a full-scale IC3 train in

Table C.1: Distribution of people in the reference scenario and mixed scenario, the demographic profile of Denmark, (Agerskov & Bisgaard, 2013), (Bengtsson, 2008, and number of participants recruited from each subpopulation (n) and the mean unimpeded free walking speed horizontally.

Subpopulation	Scenario Ref	Scenario Mix	Demographic profile of Denmark	n	Mean speed $[m/s]$
Able-bodied (16-64 years)	46(39)	28	64.5%	58	1.69
Elderly (65+ years)	-	8	18.1%	12	1.43
Hearing impaired	-	3	1.4%	3	1.81
Cognitive impaired	-	2	6.7%	4	1.55
Visually impaired	-	2	0.8%	2	1.53
Reduced mobility	-	3	7.4%	3	1.02
Children (<16 years)	-	-	17.4%	-	-

a tunnel. The train has a capacity of 23-seated and 13 standing passengers in the carriage, and further 10 standing passengers in the entrance lobby, see Fig. C.2. The longest evacuation route is approximately 24 meters. The exercises are initiated with a spoken warning message informing passengers to evacuate the train immediately. The experiment is performed without the influence of fire hazards such as smoke, heat or flames. The individual total egress time is then measured as the time from the completion of the message until the person has left the transversal tunnel.

During the experiment two different compositions of the test group were applied - homogeneous of able-bodied adults (scenario 1) and mixed (scenario 2). The composition of the test groups was matched as close as possible to the demographic profile of Denmark, however excluding children, (Agerskov & Bisgaard, 2013), (Bengtsson, 2008). Table C.1 gives an overview of the number of person for each type of subpopulation in the two scenarios. The mean unimpeded walking speed for each sub-group is also given in Table C.1 together with the number of recruited participants. These walking speeds serve as input to the STEPS model. Each scenario was replicated five times resulting in a total of 10 evacuation exercises. The participants were not familiar with the test location and received oral information prior the experiments about the procedure. The experiments were recorded with temporarily in-stalled 54 video cameras. The total evacuation time for each of the scenarios were determined by manually register when the participants passed predetermined check points.

The internal ethical codex develop at the Department of Civil Engineering at the Technical University of Denmark is followed in the current work (Sørensen & Dederichs, 2014).

Simulation - STEPS

The modelling software STEPS 5.1 was used to simulate the evacuation exercises. The following section describes the settings used to simulate the exercises.

Constructing the model

The geometry of the train and tunnel was imported to the software to create the foundation for the simulations. The grid applied to the model is tested for grid sizes of 250 mm, 300 mm and 500 mm. Assessment of the total egress times using the three different grid sizes shows that the spread around the average total egress time overlaps each other and it is therefore not possible to determine which one is better. It has only been possible to test the grid size for the scenario where walking speeds are reduced based in the speed/distance relation. Smaller grid sizes than 500 mm entails difficulties in using the speed/density relation to reduce the walking speed. STEPS calculates the density based on the neighbouring cells to the assessed person. The speed/density is based on the curve presented in the SFPE Handbook (DiNenno, 2002), where the walking speed is 0 m/s for densities larger than 3.8 $pers/m^2$. If a smaller grid than 500 mm is applied, the density calculations results in larger densities and therefore no movement. The maximum possible density for a grid of 500 mm is 4 p/m^2. Based on the tests it is chosen to work with a grid size of 500 mm, which has entailed minor changes to the train dimensions in order to fit the grid, see Fig. C.2(a).

Agent Characteristics

The heterogeneity of the experimental population can be modelled in varies ways, e.g. body size, velocity, need of assistance, ability to negotiate terrain, group formation etc. (Christensen & Sasaki, 2008), (Schneider & Könnecke, 2012). In the current study the heterogeneity of the population is modelled based on variations in body size, unimpeded walking speed and delay times to start moving. The horizontally projected body sizes are based on the results from Predtechenskii and Milinskii (Predtechenskii & Milinskii, 1978) for people wearing mid-summer street dress, which corresponds to the time of the year where the experiments were held. The heights of the participants are determined based on the average for the Danish population and accounting for age (Hesse, 2007).

STEPS offers pre-defined default values for the walking speeds for each type of person. In the current simulations walking speeds for each subpopulation was

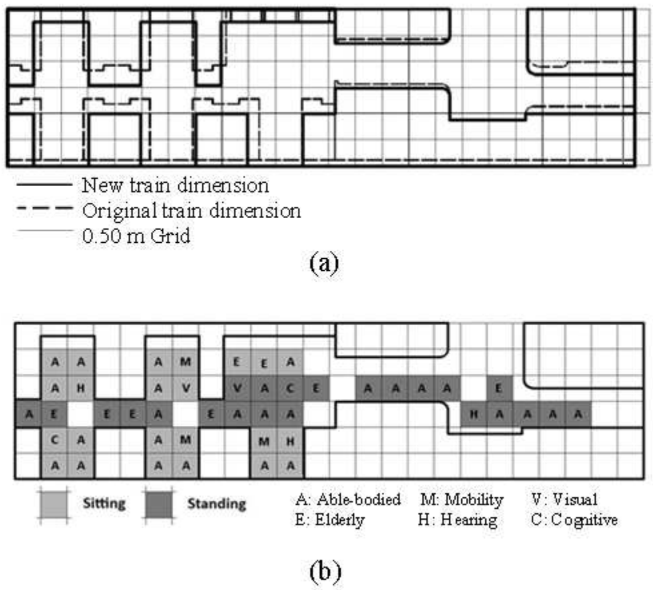

Figure C.2: (a) Modification in train dimensions based on grid size. (b) Seating of subpopulations in the train for the mixed scenario and display of the grid system.

obtained from the exercises and the measured values (Table C.1) are used as input to the model. Observed delay times from the experiment are likewise used as input, where a mean delay of 13.7 seconds is representative for all subpopulations. It is assumed that the standing agents will start moving without delay.

Agents are seated as in the experiment according to Fig. C.2(b) and assigned the free speed given in Table C.1. Thus, the default Fruin distribution is not applied, (Fruin, 1971). The seating was randomly determined for each replication of the exercises. However, the seating from the first run was used as reference for the simulations. It is chosen not to use random seating in the simulations and therefore use the exact same seating as applied in the experiment for all simulation replications. The chosen grid size implies a maximum capacity of 52 persons. However, it was chosen to follow the experimental setup and occupy the train with 46 passengers.

Modeling assumptions

Known from previous studies the walking speed is affected by the surrounding person density, (Predtechenskii & Milinskii, 1978), (Fruin, 1971), (Pauls, 1980). STEPS offer two different possibilities for walking speed reduction as a consequence of person density; one by the use of the speed/density curve given in the SFPE handbook (DiNenno, 2002), and another with the use of the interpersonal distance curve developed by Dr. Peter Thompson (Thompson & Marchant, 1995). The evacuation exercises are modelled using both these two methods to investigate the differences, and to determine which one of the options that gives the most appropriate result for a mixed population. The total evacuation flow is affected by the speed reduction methods. In addition, the flow through the train exit is controlled. Danish Guidelines provide a prescribed value of 1 p/s/m as the maximum flow through an exit, and this value is used as input for the simulations, (Erhvervs og Boligstyrelsen, 2004).

To account for variability of evacuation simulation results each scenario is ran 50 simulations. The number of simulations is based on recommendations given by the Maritime Organization for evacuation analysis of passenger ships (National Maritime Organization, 2007).

Result and Discussion

In the following section the results from the study is presented and discussed. The section is divided into two parts. The first part presents results for the total egress time for the entire population from the experiment and the two different simulations. The second part contains a detailed quantitative assessment of the individual egress times for the subpopulations.

Total Egress times

The total egress time for the complete test population is presented in Fig. C.3. The figure consists of two graphs, A and B. The left graph, A, is the total egress flow for the mixed population for the experiment and the two simulations of the same experiment. It is seen that the simulation using the speed/density relation fits the experimental result best. However, the total egress time is longer for the simulation. The three curves have similar trends for the first 30% of the exiting population after this point the curve for the experiment and the speed/density relation breaks and continues with a less steep slope.

Figure C.3B, shows the results obtained from the experiment and simulations for the reference group of able-bodied adults. It is seen that the simulation using the speed/distance relation is the most representative for the reference group. It should be noticed that the curve for the experimental results is shorter. This is due to limitations in the recruitment process and only 39 able-bodied persons were available for this scenario. The total egress time differs with 14 seconds for the 39th person. A part of the difference might be explained by the exit time for the first person, which gives an initial difference of 5 seconds. The trend for the experiment and the speed/distance-simulation is however similar and results in comparable total egress times.

The results presented in Fig. C.3 for the reference group and the mixed group shows that the simulations using the optional speed/density relation gives the best results compared with the experimental findings for the mixed population. Contrary, the optional speed/distance relation is the best fit for the reference group. On that basis, it is decided to use the speed/density relation to assess the individual egress times for the subpopulations in the mixed group.

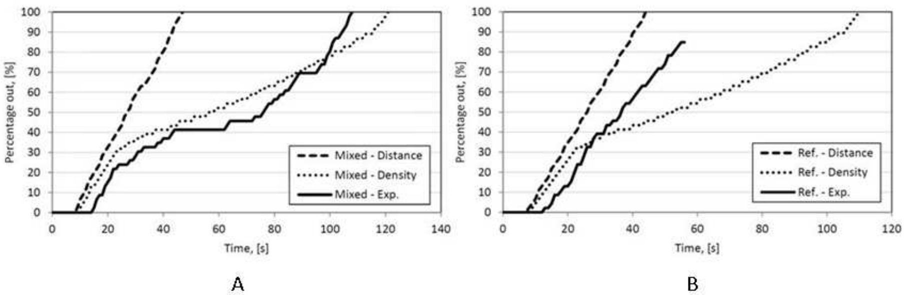

Figure C.3: Total egress flow for the mixed population (A) and the reference group (B). The black line represents the experiment (Exp.) and the dotted lines represent the simulations.4.2 Egress time for subpopulations

In the following section the individual egress times for the subpopulations are presented and discussed. The experimental results and the simulation using the speed/density relation are compared. In cases where differences between the experimental results and the simulations are detected the cause are evaluated based on the video recordings from the experiment.

Figure C.4 presents the results for the chosen four subpopulations: hearing (A) and mobility (B) impaired test per-sons, elderly (C) and able-bodied test persons (D), respectively.

The individual egress times for the three hearing impaired participants are presented in the middle left graph in Fig. C.4(A). It is seen that the difference between the simulation and experiments is two and five seconds respectively for the first and second person. For the third and last person there is detected a difference of six seconds between the experiments and the simulation. For the first person the simulation predicts a faster egress time compared to the experiments, however the difference is negligible. The simulation predicts a longer evacuation time for the remain-ing two agents. Overall, the total egress time for the three hearing impaired participants are comparable between the simulation and the experiment.

The graph to the right in the middle of Fig. C.4(B), presents the egress flow for the three persons with reduced mobility. The first person exits two seconds faster in the experiment compared to the simulation. The following two persons exit the tunnel 13 and 18 seconds faster in the experiments compared to the simulation, respectively. All three participants are initially positioned in the carriage. The characteristics of the three participants with reduced mobility differ. One is using crutches and takes up space in the egress path, which restricts overtaking and queuing is therefore formed. The two other persons are leg amputated and their body sway during movement is larger com-pared to the other participants in the experiment. Assessing the video recordings, it is found that the mobility impaired person, using crutches is the first of the three to exit the tunnel. The second mobility impaired person is caught within the queue formed by the first person. This might explain the faster evacuation time for the second person. The third and last participant is not enclosed in the first queue and is himself subject for formation of a queue. None of the three participants received assistance from a fellow participant during horizontal movement. However, the one with crutches receive help to negotiate the stair.

The bottom left graph in Fig. C.4(C), shows the exit flow for the subpopulation consisting of elderly participants. The individual total egress time for the first three members of this group is comparable for the simulation and experiment. The difference is in the range of seven seconds between the experiment and simulation, which is considered reasonable. The fourth person exit the tunnel after 80 seconds in the experiments compared to 40 seconds in the simulations. This indicates that something in the total flow has influenced the fourth person and consequently the rest of the flow of elderly people. Examining the video footage it could be seen that the first three persons exit the tunnel before the mobility impaired participant with crutches, who causes the formation of a queue because he uses the whole width of the egress path, and is not overtaken by anyone. Even though there is a time span of 42 seconds in the experiment where no elderly people are exiting, the final difference between the simulation and experiment is 13 seconds. It is seen from the graph that the time interval between the persons in the simulations is much more constant compared to the experiment. On the other hand the queuing in the experiment results in very small time interval for the fourth to the sixth persons. These three persons exit within 5 seconds. The last two persons, seven and eight, are positioned in the queue formed behind the second mobility impaired person and they exit within a time span of 2 seconds. The exit times are more evenly distributed in the simulations compared to the experiments, where individual behaviour influences the total evacuation flow.

The last graph, bottom right in Fig. C.4(D), shows how the able-bodied adults exit the tunnel. The first person exits after 10 seconds in the simulation com-

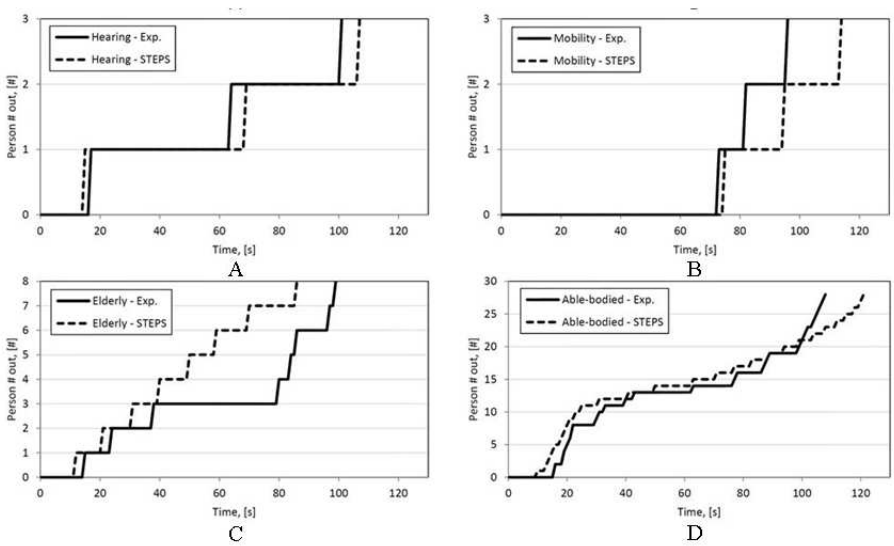

Figure C.4: Individual egress times for each of the four subpopulations. The black represents the experiment and the dotted line the average simulation. A: Hearing. B: Mobility. C: Elderly. D: Able-bodied.

pared to 16 seconds in the experiment. This difference is sustained until the eighth person has left the transversal tunnel. After the eighth person has evacuated, there is observed a plateau for the experimental curve, a time span where no one exits. From the video recordings two reasons for this first plateau are detected. First, the eighth able-bodied adult is the last person situated in the entrance lobby, and the ninth person is therefore situated in the carriage. Second, a cognitive impaired participant controls the first part of the flow from the carriage, due to his/her slower walking speed. She places both feet on every stair tread, which is the reason for her velocity. Furthermore, no overtaking is observed. Longer plateaus are likewise observed between the 13th and 14th able-bodied and again between the 14th and 15th person. The cause of the first plateau is found in the video recordings to be the first mobility impaired participant who occupies the stair and is subject for a queue formation. There are no specific incidents that can be addressed as a reason for the second plateau. The last ten persons in the experiment exit within a time span of 10 seconds, which corresponds to 1 p/s, which is considered reasonable. In the simulation it takes 38 seconds for the last ten persons to evacuate, and this is the reason for the difference in total egress time.

The results show that in three out of four sub-populations the simulations give a conservative total egress time for the subpopulations respectively. However, STEPS is not capable of predicting the interactions and differences in behaviour observed in the experiments.

None of the available sub-models provided in STEPS are capable of taking into account the altruistic behaviour observed in the experiments. The results from the current study show differences in the egress flow for the subpopu-lations between the simulation and experiment. The heterogeneity of the population is seen to have an influence on the evacuation flow. The amount of data is still scarce for vulnerable people even though there have been an increasing focus on this population in the past decades. It is therefore important that engineers and designers do not fully rely on results from simulations when predicting the evacuation of buildings and other structures. Attempts to create an on-line database with data on human egress behaviour are made within the last ten years. Such database could serve as a tool for designers, modellers, engineers, fire consultants etc. to increase the reliability of and development of evacuation models, (Gwynne, 2013). Hence, representative data might produce a stronger bond between simulations and real emergencies.

Various aspects of human behaviour (discussed elsewhere) were neglected in the modelling.

The participants recruited were taking part in more than one exercise during the day of the experiment. It is therefore assumed that personal relationships among the members of the different subpopulations were established and have affected the results. The optimum experimental setup would be a completely new cast for each replication of the exercises.

Conclusion

The influence of the composition, with altering heterogeneity of the population on egress times during real fire drills were investigated in the current work. The results were compared to the total escape times using the software STEPS. Besides able-bodied adults, members of the reference group, the participating population consisted of sub-populations covering hearing, visually, mobility and cognitive impaired people as well as elderly people. The study has the following findings:

The total egress times from the experiments are twice as long for the mixed groups as for the able-bodied group. The application of the, in the STEPS manual, speed/distance relation does not give conservative predictions of the total egress times in both cases. However, it results in better predictions for the able-bodied group, compared to the mixed population. Results found, when applying the speed/density relation in STEPS that this matched best with the experimental results for the mixed test population. Hence, the speed/density relation was used to assess the individual egress times for the subpopulations in the mixed group.

Assessing the results in relation to the speed/density relation, the individual egress times for the subpopulations in the mixed group leads to the following findings:

The model over-predicts the egress times for five of the six subpopulations except for the elderly subpopulation in the evacuation process of the heterogeneous group. The egress time of the visually impaired sub-population is affected by the assistance by an able-bodied adult, guiding the impaired person, and letting them pass freely. The egress time for the hearing-impaired subpopulation was affected by queuing in the heterogeneous group. Further-more, the total flow was affected by mobility-impaired participants due to walking speeds horizontally and on stairs as well as lower densities due to the movement and the use of crutches. Overtaking was rarely observed in the heter-ogeneous group. However, overtaking was observed in the simulations. In addition, assistance by able-bodied adults led to an increase in the speed of the impaired subpopulation. Overall the results indicate that it is necessary to account for heterogeneity, when describing the evacuation of mixed populations. The first step of using corresponding input velocities of the subpopulation leads to a reasonable description of the evacuation, but not a conservative prediction of the total egress times. Furthermore, it appears that human behaviour and the processes affect the flow and the total times.

Acknowledgements

The authors would like to thank the Interreg IV A Öresund Kategat Skagerak program, the European Union and Trygfonden.

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Appendix D

Walking speeds on horizontal planes and descending stairs for blind and visual impaired people

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Type	Conference Abstract
Title:	**Walking speeds on horizontal planes and descending stairs for blind and visual impaired people**
Author:	J.G. Sørensen and A.S. Dederichs
Conference:	Fire Safety Day 2012
Date:	April 18, 2012
Location:	Lund, Sweden

Abstract

According to a newly published report from the World Health Organization and The World Bank, it is estimated that over 1 billion people are living with a disability (World Health Organization, 2011) corresponding to 14,2% of the world's population. Hence, it is important to consider this part of the population when dealing with fire safety of buildings.

Introduction of the performance based fire safety codes gives the opportunity to design much more complex buildings which have difficulties fulfilling the requirements given by the prescriptive codes (Hadjishophocleous & Bénichou, 2000). The safety level in buildings can then be proved by use of calculation on the time to evacuate the building and the time until tenability criteria's are reached.

The theory used for the determination of the evacuation time is primarily based on able-bodied people. However, studies have shown that a considerably part of the population have a temporarily or permanent kind of disability, and this part is more likely to suffer during emergency situations (Manley, Kim, Christensen, & Chen, 2011). The recent decades increasing focus on accessibility to buildings imply that people with disabilities are present and need to be considered, while calculating the time for evacuating a building. However, adequate accessibility of a building is not an insurance of egressibility (Papaioannou, 2006). Previous studies have investigated the prevalence, type and mobility of disabled people as wells as the walking speeds horizontal and on inclined planes (Boyce, Shields, & Silcock, 1999a), (Boyce, Shields, & Silcock, 1999b).

The present study concentrates on walking speeds on horizontal planes and descending stairs for the section of blind and visual impaired people. Data on walking speeds are collected through various evacuation exercises. There have been performed single and group evacuation exercises as well as two full scale exercises. The exercises were carried out at four different buildings, where the participants were familiar with the environment. All primary escape routes including corridors and stairs were filmed with video cameras and the films were afterwards used for analysis of the walking speeds and densities.

The walking speeds are determined for low densities less than 1 $pers/m^2$ on horizontal planes and for increasing densities for both horizontal planes and descending stairs. This distinction is made due to the values provided by national guidelines. The result shows that the average walking speed at low densities on horizontal planes is less than the value provided by guidelines in e.g. Denmark, Sweden and USA (Erhvervs og Boligstyrelsen, 2004) (Boverket, 2006) (Bryan, 1997).

According to Nelson and Mowrer (Nelson & Mowrer, 2002) the walking speed

on horizontal planes de-creases linearly as the density increases. Results from the current study show the same tendency, but the obtained results are shifted downwards compared to the theoretical relation. This means that blind and visual impaired people have a lower initial speed compared to able-bodied people, which was also the case at low densities. However, the slope of the tendency line is within the same range.

The walking speed descending stairs is likewise decreasing linearly as the density increases according to the theory. Results from the present study show that the initial speed is lower than the theoretical value. The pace with which the walking speed decreases for increasing density is much lower compared to the theoretical value for able-bodied people.

These results indicate that the walking speeds for blind and visual impaired people are lower than for able-bodied people. The theory of Nelson and Mowrer is not conservative when applied for the description of the evacuation capability of this section of the populations.

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Appendix E

Evacuation Characteristics - Is there a difference between homogeneous and mixed groups?

Type	Conference Abstract
Title:	**Evacuation Characteristics**
	Is there a difference between homogeneous and mixed groups?
Author:	J.G. Sørensen and A.S. Dederichs
Conference:	Fire Safety Day 2013
Date:	April 17, 2013
Location:	Kgs. Lyngby, Denmark

Abstract

Performance based fire safety codes have been implemented in many countries around the world. Implementation of these codes has induced more complex building constructions or landmarks such as Burj Khalifa in Dubai, The Shard in London or The Bird's Nest in Beijing. Also ordinary buildings such as office buildings are becoming more complex due to an increasing demand on spectacular and state of the art buildings. These complex buildings have challenged fire safety engineers because standard solutions cannot be applied. On the contrary it gives the opportunity to be innovative and develop new solutions. However the safety level in the building should still be sufficient according to current regulation. Fire safety engineering tools including various models to predict evacuation times and different software to calculate time until critical conditions occur have been developed. The majority of the data that creates the foundation for the evacuation models is based on able-bodied adults and are collected for more than 30 years ago (Fruin, 1971) (Predtechenskii & Milinskii, 1978) (Pauls, 1980). In addition characteristics of the population have changed since (Harish & Verma, 1996) (Kaya, 2002). Furthermore homogeneous groups of able-bodied adults do rarely occur in the building environment. Evacuation data on representative heterogeneous groups comprising children, able-bodied males and females, elderly people and people with impairments are therefore needed to establish a valid foundation for prediction of evacuation times.

This study attempts to clarify the differences in individual behavioral patterns and total evacuation times for a homogeneous group of able-bodied adults and a heterogeneous group with a composition corresponding to the demographic profile of Denmark.

A series of 20 full-scale evacuation experiments with varying composition of the test sample was conducted in Denmark in May 2012. The experiments were performed from an IC-3 train inside a tunnel corresponding to the rail connection between Zealand and Funen - The Great Belt link. The capacity of the train was 46 passengers, where 23 were seated and 13 were standing in the carriage and additional 10 were standing in the corridor between the entrance and the carriage. The experiments were initiated by a spoken warning message telling that smoke was observed outside the train and that passengers should evacuate immediately. The egress path was from the train to the main tunnel, from the main tunnel to the nearest transversal tunnel, and here to the safe place outside the tunnel. During the experiments participants were not exposed to any extra ordinary conditions such as smoke, heat or flames.

Results from the present study clearly show that the total evacuation time is doubled for the mixed groups compared to the homogeneous group. It is therefore evident that the composition of the population in a building matters

for the total evacuation time. In addition this finding needs to be considered while designing the safety level of buildings, especially for buildings where it is probable that all types of people are present. The detected differences in individual behavioral patterns for the homogeneous and heterogeneous groups will be further explained and discussed in the proposed presentation.

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Appendix F

Equal access - equal egress: Accounting for people with disabilities in emergency situations

Type	Conference Abstract
Title:	**Equal access - equal egress**
	Accounting for people with disabilities in emergency situations
Author:	J.G. Sørensen and A.S. Dederichs
Conference:	NNDR - 12^{th} Research Conference
Date:	May 30-31, 2013
Location:	Naantali, Finland

Abstract

Accessibility to buildings for all persons independent of their (dis-)abilities is required by law in many countries (the Swedish BBR 3, the Danish BR10:3:2). However, accessible buildings are not automatically egressible in case of a fire. The fire safety design is based on escape routes, and numerical evacuation models are applied for the prediction of the evacuation process in the fire safety design. In many cases these models are best fit to describe a normative description of the population comprehending young able-bodied adults. It has been shown, that some models poorly describe populations, other than able-bodied adults (Ulriksen & Dederichs, 2012, Sørensen & Dederichs, 2012). Hence, the safety level in buildings for the vulnerable groups might not be the same as for able-bodied adults. Furthermore, it has been shown that people with disabilities are more frequently hurt in fires (Papaioannou, 2006). It is essential to use models, enabling the prediction of the egress of a total population in a building. In the current quantitative and qualitative study evacuation times and -characteristics from a train in a tunnel are measured for a full-scale evacuation exercise. The results are compared to times determined with a computer simulation of the exercises. The full-scale experiment involved 46 participants, where the composition of the test population corresponded to the demographic profile of Denmark, including children, able-bodied adults, elderly people and people with different types of impairments. Four different exercises were performed, altering the composition of the test population. The effect of the inclusion of different groups on evacuation times was investigated.

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Appendix G

Evacuation of blind and visually impaired Americans - An evacuation study on the ability to self-evacuate

Type	Conference Abstract
Title:	**Evacuation of blind and visually impaired Americans**
	An evacuation study on the ability to self-evacuate
Author:	J.G. Sørensen
Conference:	Fire Safety Day 2014
Date:	June 12, 2014
Location:	Kgs. Lyngby, Denmark

Abstract

During the past decades there has been an increasing focus on civil and human rights for people with disabilities [1]. The increased focus has induced changes in the way buildings are designed. Buildings need to be accessible to everyone and need to be safe as well. Since buildings has become more accessible to people with disabilities it is important that the safety design of a building follow the requirements this segment of the population have in case of an emergency and evacuation. In addition, people with disabilities are considered more vulnerable in an emergency [2].

Meanwhile design of buildings has become more complex and spectacular. These complex building is difficult to design using prescriptive building codes and performance based has been developed. Likewise performance based fire safety codes have been developed [3]. These codes allow the fire safety engineer to use engineering software tools while designing the fire safety system of a building. Regarding evacuation the software tools need input to give representative estimates. The majority of data available are based on able-bodied adults and there is a lack of data for the vulnerable segments of the population. When data on parts of building occupants a missing it is questionable if the estimates are representative for the current building.

The aim of the current study is to perform a series of evacuation experiments with blind and visually impaired Americans to gather data on their evacuation characteristics. The characteristics of interest are walking speeds horizontally and descending stairs as well as human behavior and interactions with the other evacuees and the building environment. These experiments are a supplement to a Danish study conducted in 2011. Evacuation experiments were conducted in a traditional office building in Washington DC, USA, in collaboration with National Fire Protection Association, Boston, USA. The experiments consisted of five different runs with different sizes and composition of the test groups. In total 11 participants took in the experiments. The participants were instructed in the egress path before the experiments which might have influenced the results. After the experiments the participants were interviewed about their use of the building types in general and the barriers they meet.

The analysis of the experiments and the interviews revealed the following findings:

- The free walking speed horizontally was comparable to values provided in international guidelines.
- There was detected a difference in horizontal walking speed for people with and without guide dog.

- Walking speed descending stairs was lower than for able-bodied adults and for increasing densities the majority of data points was situated below the N&M model.
- Walking speed was dependent on other participants in the flow.
- Blind and visually impaired people frequent a large variety of building types.
- The most common barrier in the building environment is illogical interior design and unpredictable layouts.

It is concluded from the study that the evacuation characteristics and behavior for people with visual impairments are different from able-bodied people. As a consequence the building designer and fire safety engineer needs to draw attention to the special requirements and needs this segment of the population have during normal use of the building as well as during emergencies.

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3 Hadjisphocleous G.V., Bénichou N., Development of Performance-Based Codes, Performance Criteria and Fire Safety Engineering Methods, International Journal on Engineering Performance-Based Fire Codes, 2000,Volume 2, Number 4, p127-142

Appendix H

Från tillgänglighet i - till evakueringssäkerhet från byggnader.

Type	Conference Abstract and Poster
Title:	**Från tillgänglighet i - till evakueringssäkerhet från byggnader**
Author:	J.G. Sørensen and A.S. Dederichs
Conference:	HAREC dagen
Date:	November 27, 2012
Location:	Malmö, Sweden

Abstract

Tillgänglighet för personer oavsett funktionsnedsättning är ett lagkrav i Sverige och Danmark (BBR 3, BR10:3:2), en rättighet det har arbetats på i många år inom byggnads design. Olika metoder finns och används i dag för evaluering av tillgänglighet av olika byggnadstyper så som hotell (Bendel, 2006) bostäder eller andra byggnader (Iwarsson & Slaug, 2010). Handicap definieras inte längre som en karakteristik av en person med en funktionsnedsättning, men närmare som en karakteristik av den struktur eller byggnad som begränsar den funktionsnedsatta personen. Detta har lett till en nytänkande i design och en ökad närvaro av personer med funktionsnedsättning i alla sorts byggnader.

Att designa en tillgänglig byggnad implicera inte att designa en byggnad som är lika tillgÃ¤nglig i fall av brand. Fire Safety Design baserar på att beskriver tidslinjen for brandens utveckling i en byggnad och hålla dessa tider upp emot tider för evakueringen, som fås av evakueringsmodeller, som ofta bygger på en normativ beskrivning av befolkningen. I dag fattas en stor del data för vissa persongrupper, så som för personer med funktionsnedsättning. Detta gör att modellerna inte omfattar dessa persongrupper, som oftast är långsamer (Ulriksen & Dederichs, 2012, Sørensen & Dederichs, 2012) än förutsett av befintlig evakuerings teorier. Konsekvensen kan vara att dessa grupper inte är lika säker i en byggnad. Funktionsnedsatta drabbas oftare i fall av brand (Papaioannou, 2006). Ibland planeras det inte för en evakuering av dessa personer, men en räddning, som först händer när Räddningstjänsten är kommit till och i byggnaden och detta kan vara sent i brandförloppet.

I detta projekt fokuseras på evakuering av en tunnel. Evakueringen från et tågsätt i en tunnel av olika blandningar av befolkningen testats. I första setup evakuerades endast personer mellan 20-60 år utan funktionsnedsättning. I andra evakuerades en persongrupp, som omfattade barn, pensionister och personer med en rad fysiska och psykiska funktionsnedsättningar. Resultaten har visad en stor skillnaden i evakueringstiderna. Populationens samansättning är betydande för evakueringstiderna.

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DTU

Från tillgänglighet i - till evakueringssäkerhet från byggnader.

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Introduktion

Brand har altid været forbundet med farer og er det stadig i dag, idet menneskeliv hvert år går tabt som tilfælde heraf. Vi opholder os i bygninger i hovedparten af vores levetid og ønsker derfor at bygningerne, som vi opholder os i, yder os beskyttelse mod diverse farer. I gennem de seneste årtier er de bygninger, vi opholder os i blevet mere og mere komplekse. Det har derfor givet store udfordringer for ingeniørerne der skal sørge for at bygningerne yder den tilstrækkelige beskyttelse og sikkerhed også i tilfælde af brand.

Brandsikkerheden i en bygning kan eftervises ved brug af beregninger, som foretages ved hjælp af modeller for evakuering samt brandens dynamik. Resultaterne fra disse modeller sammenlignes og den krævede tid til evakuering skal være mindre end den tid det tager før der opstår kritiske forhold. Resultaterne, som modellerne er baseret på, afhænger i høj grad af inputtet. Input data til de fleste modeller, som findes i dag, er hovedsageligt baseret på voksne personer uden funktionsnedsættelser. Dette er dog ikke repræsentativt for den sammensætning der er af personerne i en bygning og befolkningen generelt. Der findes begrænset mængde af data for personer med funktionsnedsættelser, selvom reglerne foreskriver, at de skal opnå samme sikkerhed i bygninger, som personer uden funktionsnedsættelser.

Tilgængelighed vs. Evakuering

Tilgængelighed for personer, uafhængigt af funktionsnedsættelse, er et lovkrav i både Sverige og Danmark (BBR 3, BR10:3:2), og en rettighed som der er kæmpet for i mange år. Forskellige metoder findes og anvendes i dag for at vurdere tilgængeligheden af forskellige bygningstyper såsom hoteller (Bendel, 2006), boliger og andre bygninger (Iwarsson & Slaug, 2010). Samtidig er der krav til at brandsikkerheden af bygningen er tilfredsstillende for alle, som opholder sig i bygningen. Dette gælder således også personer med funktionsnedsættelser, idet de er sikret adgang til bygninger grundet kravene til tilgængelighed.

Tilgængelighed, det vil sige det at komme ind i en bygning, kan dog ikke direkte sidestilles med det at komme ud af bygningen, hvis der skulle opstå en brand. Et klassisk eksempel er brugen af elevatorer i forbindelse med brand. I mange bygninger må en elevator slet ikke anvendes under brand. Men hvordan skal personen i kørestol på fjerde sal, som er kommet ind i bygningen ved at bruge elevatoren, komme ud hvis det brænder? Bygningen er jo fuldt tilgængelig for vedkomne, men den frie bevægelighed i bygningen indskrænkes i tilfælde af brand. Det er derfor vigtig at undersøge, hvilke personer der er i en bygning i forbindelse med brandsikring af denne. Endvidere er de data som i dag er tilgængelige til brug ved brandteknisk dokumentation baseret på voksne uden funktionsnedsættelser.

Metode

I dette projekt er der udført en række evakueringsforsøg med i alt 46 blinde og svagsynede. Deltagerne var rekrutteret fra forskellige nationale organisationer og centre for blinde og svagsynede. Deltagernes grad af synsnedsættelser blev evalueret ud fra den danske klassifikation af synsstyrken, hvor klasserne A (6/18-6/60), B (6/60-1/60), C (<1/60) og D (ingen lyssans uden projektion) anvendes. Klasse A er personer med det bedste syn, mens klasse D er personer, som er helt blinde. Forsøgene fandt sted i deltagernes naturlige miljøer, hvor de var vant til at færdes. Forsøgene var opdelt i tre niveauer: single evakuering, gruppe evakuering og fuldskala evakuering.

Data blev indsamlet ved hjælp af midlertidigt opsatte kameraer, som var placeret på strategisk udvalgte steder i bygningerne, hvor forsøgene blev udført. Der blev anvendt mellem 25 og 50 kameraer for at indsamle data. De indsamlede data er efterfølgende blevet analyseret. Analyse af densitet (antal personer pr. m^2) er foretaget på baggrund af et referenceareal på 2 m^2, svarende til 1 meter foran og bagved den pågældende person samt 1 meter i bredden omkring personen.

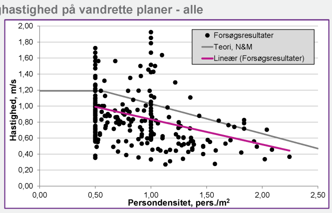
ETIK

Efter dansk praksis er projektet anmeldt til datatilsynet, idet personer kan identificeres på de optagede film ud fra helbredsmæssige oplysninger. Forsøgene er ikke anmeldt til videnskabsetisk komité, idet register forskning, interview undersøgelser og observationsstudier ifølge dansk praksis er undtaget anmeldelsespligten så længe der ikke indgår biologisk materiale i forsøgene.

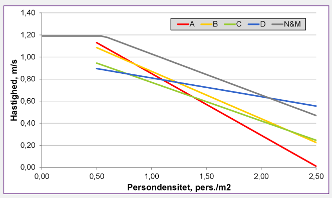
Resultater

Graferne nedenfor viser de resultater, som er opnået for ganghastigheder på henholdsvis vandrette planer og ned af trapper. Resultaterne er vist for den samlede gruppe af blinde og svagsynede samt med en differentiation på graden af synsnedsættelse for ganghastigheder på vandrette planer.

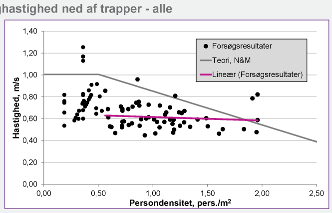
Ganghastighed på vandrette planer - alle



Ganghastighed på vandrette planer - kategorier



Ganghastighed ned af trapper - alle



Konklusion

Forsøgene har vist at:

- **Personer med synsnedsættelser går langsommere på vandrette planer end voksne personer uden funktionsnedsættelser.**
- **Ved stigende persondensitet (antal personer på en m^2) kan personer med størst synsnedsættelse opretholde en højere ganghastighed på vandrette planer sammenlignet med voksne personer uden funktionsnedsættelser.**
- **Ganghastigheden på trapper er for blinde og svag synede tilnærmelsesvis konstant ved en stigende densitet. Dog ligger hovedparten af målepunkterne under den teoretiske værdi baseret på voksne personer uden funktionsnedsættelser.**
- **Den teoretiske værdi, som oftest anvendes for ganghastigheder ved evakueringsberegninger, er ikke konservativ når personer med synsnedsættelser betragtes. Der kan derfor stilles spørgsmålstegn ved om denne gruppe af mennesker er sikret et tilstrækkeligt sikkerhedsniveau i bygninger.**

Referencer:
BBR, Boverkets Byggregler, kapitel 3, Tillgänglighet, svensk.
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Appendix I

Schematic Drawing of Locations

The following figures present schematic drawings of the egress routes used at the six locations.

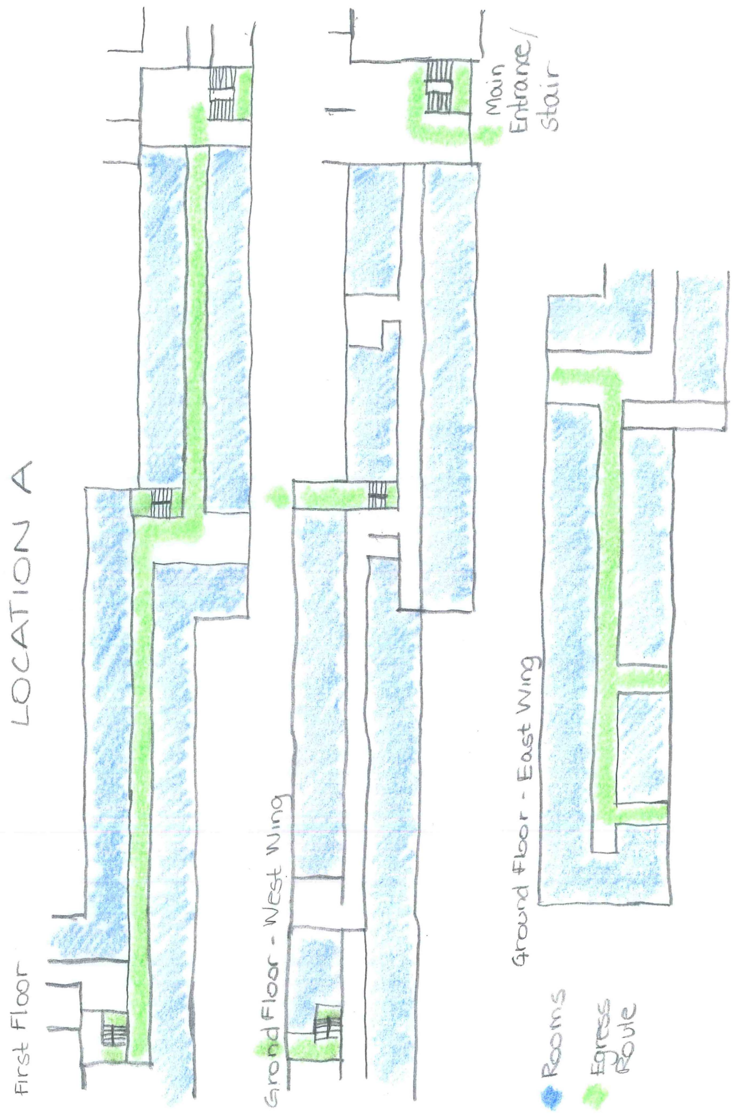

Figure I.1: Emergency Route - Location A

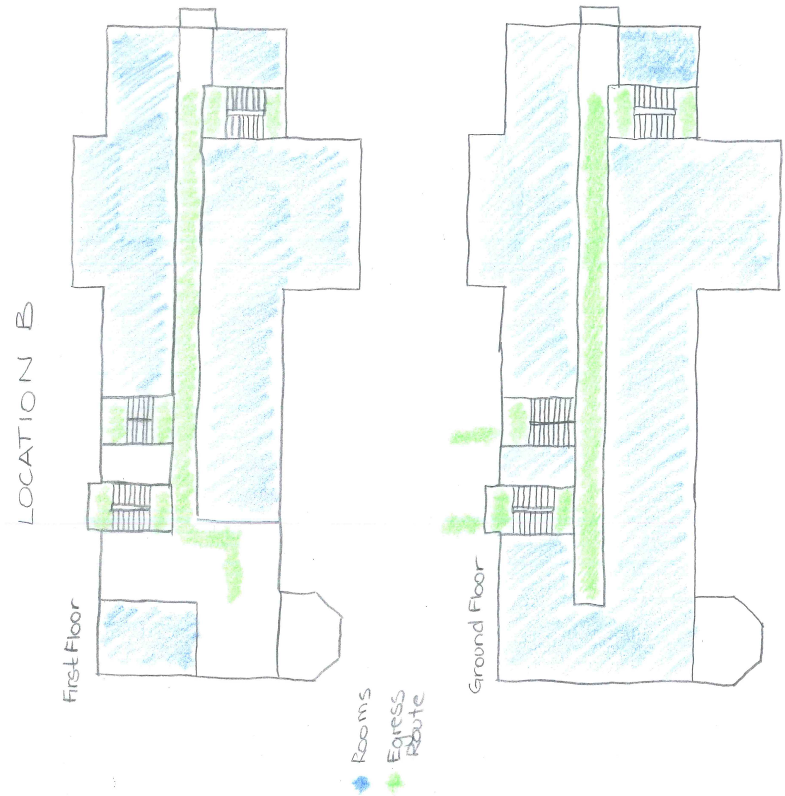

Figure I.2: Emergency Route - Location B

Figure I.3: Emergency Route - Location C

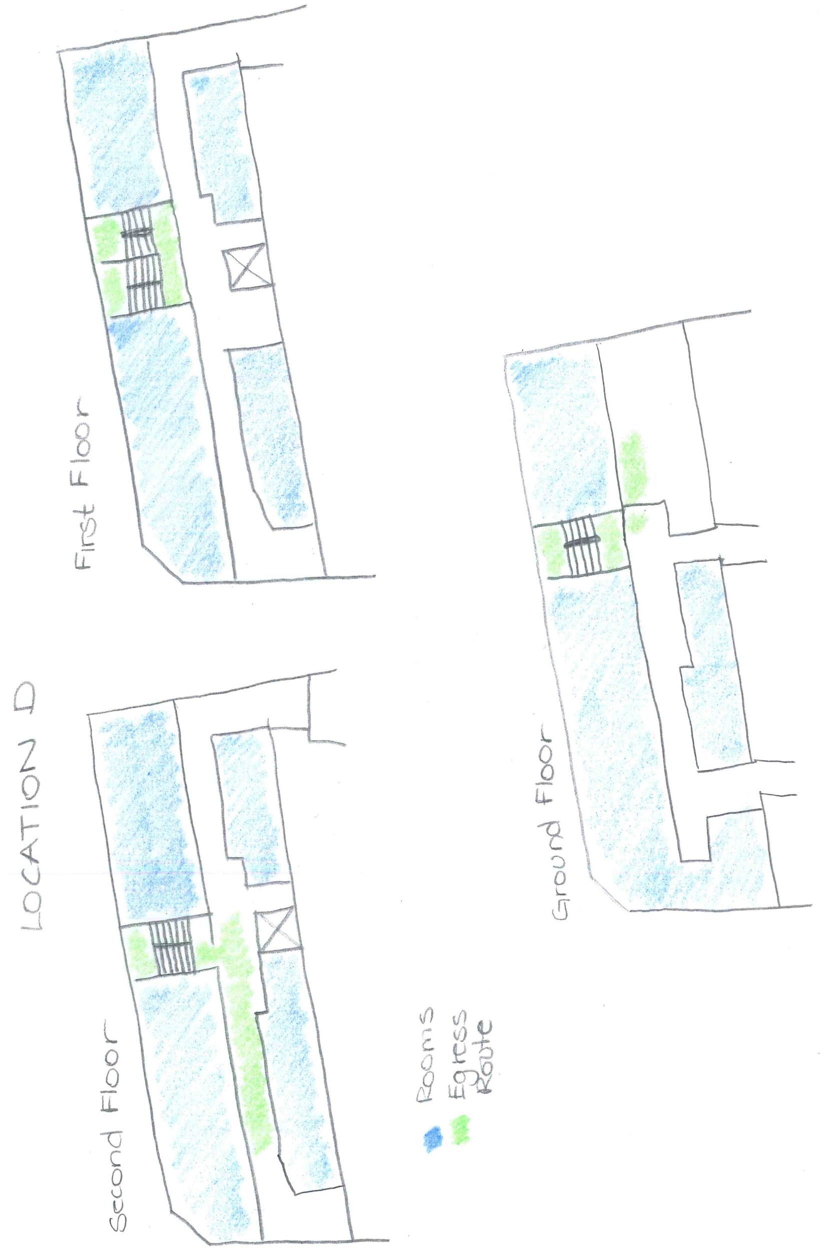

Figure I.4: Emergency Route - Location D

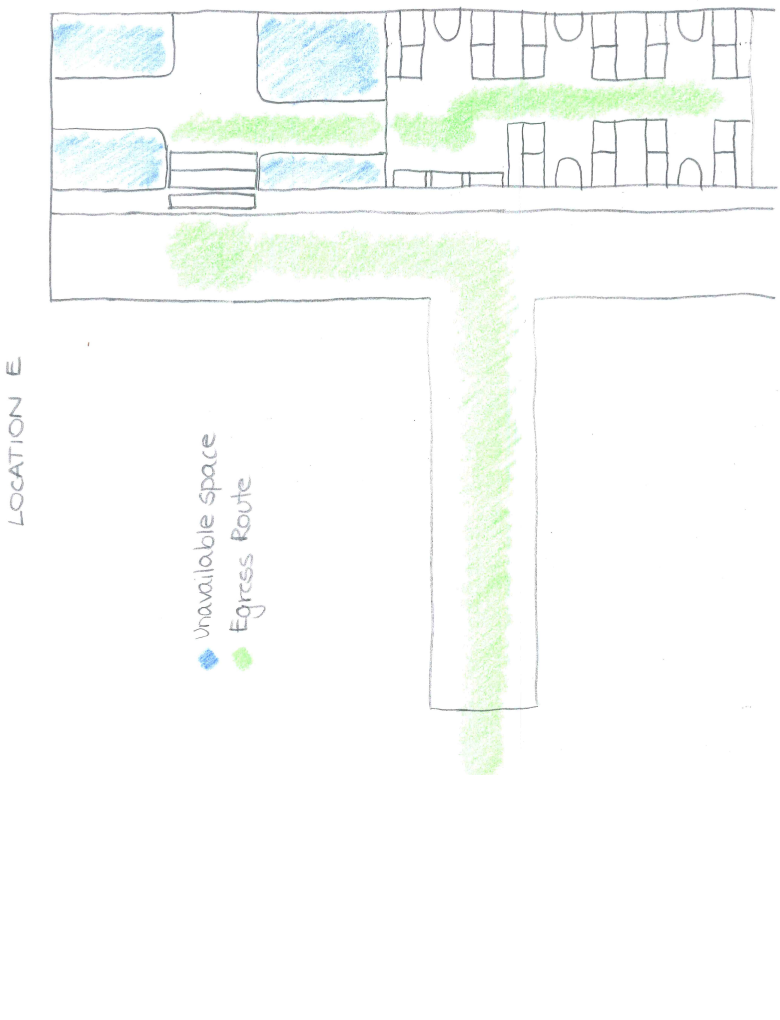

Figure I.5: Emergency Route - Location E

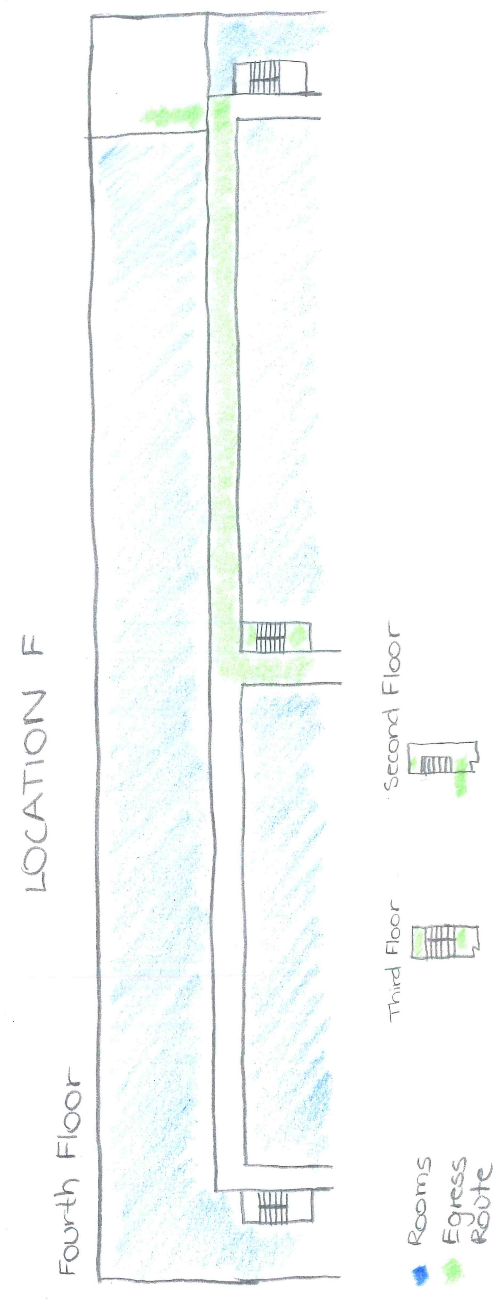

Figure I.6: Emergency Route - Location F

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Appendix J

Internal Ethical Codex - DTU BYG

Ethical Codex for evacuation experiments involving human beings and conducted by DTU BYG

Buildings become bigger, more spectacular and more complex. The increased complexity entails high challenges for the safety level. Consequently, the fire safety engineer faces new challenges. Different tools are developed to solve the challenges and different software can be used to for instance estimate total evacuation times. However, these tools need input. Scientific evacuation experiments deliver such input. The majority of data are collected more than 30 years ago and the process of designing and build buildings have changes since that time. Hence, it is very important that the data reflect the occupants present in buildings. Evacuation experiments are performed reflecting reality as close as possible. However, performing experiments involving human beings entail ethical considerations.

Purpose

The aim of this codex is to create uniform guidelines for evacuation experiments conducted by DTU BYG. The codex shall ensure the rights for the participants in the experiments. In addition, the codex shall ensure that participants receive uniform necessary information about the experiment.

Codex for evacuation experiments

1. Evacuations experiments and project conducted at DTU BYG always need approval from the Ethical Committee and the Danish Data Protection Agency.
2. Participants shall always receive written and oral information about the aim of the project and method. The written information shall include information and background for the experiment, an experimental plan, side effects and risks, economics and access to experimental results. Template available via Campusnet or supervisor.
3. Participants need to fill out an informed consent before taking part in experiments.
4. Participants can withdraw their consent any time during the experiments without explaining the reasons.
5. Participants are guaranteed full anonymity.
6. Participants may not gain any economical profit from participation, though mileage allowance and food and drinks might be given in relation to the experiment
7. Participation is completely voluntary and participants can withdraw any time.
8. In unannounced evacuation experiments participants must immediately after the experiments are completed give their consent to use data in research.

Appendix K

Scientific Report - Evacuation of blind and visually impaired Americans

Type	Scientific Report
Title:	**Evacuation of blind and visually impaired Americans**
Author:	J.G. Sørensen

DTU Civil Engineering

Evacuation of blind and visually impaired Americans

An evacuation study on the ability to self-evacuate

Janne Gress Sørensen

2013/2014

Evacuation of blind and visually impaired Americans
An evacuation study on the ability to self-evacuate

Report
2013/2014

By
Janne Gress Sørensen

Preface

This report is prepared as a result of a series of evacuation experiment conducted as a part of the authors external research stay at National Fire Protection Association, Boston, USA. The research stay was completed as a part of the PhD Education at The Technical University of Denmark.

The report presents the results obtained from the experiments and a discussion of these. Likewise it gives an introduction to the topic evacuation of people with visual impairments and a description of the method used to gather data on evacuation characteristics for this segment of the population. Based on the report there will be written a scientific journal paper, which constitute a part of the authors PhD dissemination.

The experiments were prepared in collaboration with National Fire Protection Association and te US Access Board and were funded by the Danish Foundation Østifterne.

Kongens Lyngby, Spring 2014

Janne Gress Sørensen
PhD Student

Content

Resumé

I løbet af de seneste årtier har der været et stigende fokus på menneskerettigheder for personer med funktionsnedsættelser. Dette øgede fokus har forårsaget ændringer i den måde hvorpå bygninger i dag bliver designet og indrettet. Bygninger skal i udgangspunktet være såvel tilgængelige men også sikre for alle at opholde sig i. I takt med den øgede tilgængelighed for personer med funktionsnedsættelser er det vigtigt at også sikkerheden i bygninger tilgodeser denne gruppe mennesker og deres behov i en nødsituation. Ligeledes betragtes mennesker med funktionsnedsættelser som mere udsatte i forbindelse med en nødsituation.

Sideløbende er bygninger og deres design blevet mere komplekst og spektakulært. Disse komplekse byggerier har haft udfordringer med at opfylde de præskriptive krav, som er givet lovmæssigt og derfor er der blevet udviklet funktionsbaserede regler. Der er således også udviklet funktionsbaserede brandkrav til byggeriet. Disse funktionsbaserede krav har medført at brandingeniøren har mulighed for at anvende forskellige ingeniør baserede computer værktøjer når brandsikkerheden i en bygning skal fastlægges. Med hensyn til evakuering behøver computer værktøjerne input for at kunne give et repræsentativt resultat. Dog er det data som er tilgængeligt i dag baseret på voksne mennesker uden nogen funktionsnedsættelser og der er derfor en mangel på data for de mere udsatte grupper af befolkningen. Når der mangler informationer på personerne, som tager ophold i bygninger kan der stilles spørgsmål ved om resultaterne er repræsentative.

Formålet med dette studie er at udføre en række evakueringsforsøg med blinde og svagsynede for at indsamle data der beskriver deres evakuerings karakteristik. Det er hovedsageligt karakteristika vedrørende vandret ganghastighed og ganghastighed ned af trapper samt menneskelig adfærd og interaktion mellem deltagere og interaktion med bygningen. Disse forsøg er et supplement til et lignende studie udført i Danmark i 2011.

Forsøgene blev udført i Washington DC, USA, som en del af forfatterend udlandsophold hos National Fire Protection Association, Boston, USA. Forsøgene bestod af 5 forskellige opsætninger med forskellig størrelse og sammensætning af forsøgsdeltagerne. I alt deltog 11 personer i forsøgene. Bygningen hvori forsøgene blev afholdt var en traditionel kontor bygning med lange gange og nød trapper. De blev anvendt lokal varsling i bygningen og deltagerne blev instrueret i hvilken rute de skulle anvende. Efter forsøgene blev deltagerne interviewet omkring deres brug af andre bygningstyper og hvilket barriere de møder i disse bygninger.

Analysen af forsøgene og interviewene gav følgende resultater:

- Den gennemsnitlige frie vandrette ganghastighed var sammenlignelig med værdier i internationale guidelines.
- Der blev fundet en forskel i ganghastigheden på vandrette planer for personer med og uden førerhund.
- Ganghastigheden ned af trapper var lavere end for personer uden funktionsnedsættelser og ved stigende densiteter lå hovedparten af data under N&M-modellen.
- Ganghastigheden var afhængig af andre personer i evakueringsflowet.
- Blinde og svagsynede besøger en stor variation af bygningstyper.
- Den mest barriere, som blev nævnt flest gange var et ulogisk bygningsdesign og et uforudsigeligt indvendigt design.

Ud fra dette studium kan det konkluderes at evakuerings karakteristik for personer med synsnedsættelser er forskellig fra personer med normalt syn. Som en konsekvens heraf er det vigtigt at arkitekten og

bygningsingeniøren herunder også brandingeniøren er opmærksomme på de særlige behov denne gruppe af befolkning har i forbindelse med en nødsituation, men også ved den normale brug og drift at bygningen. Det forventes at dette studium vil påvirke kommende regler og vejledninger på området indenfor brandsikkerhed i bygninger således at disse også indeholder information om personer med nedsat syn.

Summary

During the past decades there has been an increasing focus on civil and human rights for people with disabilities. The increased focus has induced changes in the way buildings are designed. Buildings need to be accessible to everyone and need to be safe as well. Since buildings has become more accessible to people with disabilities it is important that the safety design of a building follow the requirements this segment of the population have in case of an emergency and evacuation. In addition, people with disabilities are considered more vulnerable in an emergency.

Meanwhile design of buildings has become more complex and spectacular. These complex building is difficult to design using prescriptive building codes and performance based has been developed. Likewise performance based fire safety codes have been developed. These codes allow the fire safety engineer to use engineering software tools while designing the fire safety system of a building. Regarding evacuation the software tools need input to give representative estimates. The majority of data available are based on able-bodied adults and there is a lack of data for the vulnerable segments of the population. When data on parts of building occupants a missing it is questionable if the estimates are representative for the current building.

The aim of the current study was therefore to perform a series of evacuation experiments with blind and visually impaired people to gather data on their evacuation characteristics. The characteristics of interest are walking speeds horizontally and descending stairs as well as human behavior and interactions with the other evacuees and the building environment. These experiments are a supplement to a Danish study conducted in 2011.

The experiments were conducted in Washington DC, USA, as a part of the authors external research stay at National Fire Protection Association, Boston, USA. The experiments consisted of five different runs with different sizes and composition of the test groups. In total 11 participants took in the experiments. The building configuration was an office building with long hallways and emergency staircases. There was used local warning in the building and the participants were instructed in the egress path. In relation to the experiments the participants were interviewed about their use of the building types in general and the barriers they meet.

The analysis of the experiments and the interviews revealed the following findings:

- The free walking speed horizontally was comparable to values provided in international guidelines.
- There was detected a difference in horizontal walking speed for people with and without guide dog.
- Walking speed descending stairs was lower than for able-bodied adults and for increasing densities the majority of data points was situated below the N&M model.
- Walking speed was dependent on other participants in the flow.
- Blind and visually impaired people frequent a large variety of building types.
- The most common barrier in the building environment is illogical interior design and unpredictable layouts.

It is concluded from the study that the evacuation characteristics and behavior for people with visual impairments are different from able-bodied people. As a consequence the building designer and fire safety engineer needs to draw attention to the special requirements this segment of the population have during normal use of the building and during emergencies. The results from the study are expected to influence future guidelines to include information on evacuation characteristics of people with visual impairments.

1. Introduction

Safety in our society, our homes and buildings are important for life quality (Parker, Barnes, McKee, Morgan, Torrington, & Tregenza, 2004), (The WHOQOL Group, 1998). If we do not feel safe in our homes and buildings we will constantly be aware of danger and hazards. It is a large psychologically burden to be aware and alert. The uttermost consequence of this state of mind is stress (Korchin, 1962). To enhance and uphold a good quality of life, safety design of our buildings needs to take into account the characteristics of the occupants. For the fire safety perspective it is today questionable if total evacuation times estimated using available data is representative. The available data is based on able-bodied people and the diversity does not include all types of occupants such as children, elderly people and people with impairments. In addition these population segments are considered more vulnerable in emergency situations.

The current study takes its starting point in safety and evacuation of people with low vision and people who are blind. The expected results will contribute to an increased focus of the evacuation ability of this segment in our population. Furthermore it is expected that the study draws attention to the special needs vulnerable people have during emergencies.

1.1 Background

Buildings are supposed to be safe for every occupant. However, accessibility does not ensure egressibility. Performance based fire safety codes allows engineers to verify the safety level in buildings by calculations. Assessment of the personal safety level can be done by comparing the required safe egress time (RSET) with the available safe egress time (ASET) and then add a safety margin. Various evacuation simulation software are capable of predicting RSET. In addition, most of the software offers the possibility to assign different walking speeds to different groups of people within the building. However, there is a lack of data for people with impairments including blind and visually impaired people. Data used as input to these models are often based on a homogeneous group of able-bodied adults (often males), which is not representative. Large groups of blind and visually impaired people are rarely observed, but to get a statistical representative amount of data, a homogeneous group of blind and visually people impaired are considered.

Throughout the last decades there has been an increasing focus on human and civil rights for people with disabilities. Nevertheless, the history of human rights can be dated back to 539 B.C. with the Cyrus Cylinder, but it was not until 1948 human rights were assembled and codified into one single document (Ferguson, 2013), (Ishay, 2004), (UN General Assembly, 1948). This happened with the adoption of The Universal Declaration of Human Rights. One of the first initiatives for specific human rights for people with disabilities was undertaken in the United States of America. In 1990 the Americans with Disability Act were signed into law, and are the most comprehensive piece of legislation in the United States that prohibits discrimination of people with disabilities and give them the opportunity to live a mainstream American life. Australia passed on their Disability Discrimination Act 1992 in 1992, which provides protection for everyone against discrimination based on disability. This act encompasses the individual person who is treated unfairly due to a disability but also the person's relatives, friends, carers, co-workers or associates. In United Kingdom a similar Disability Discrimination Act was passed on in 1995. In the same year India adopted their Persons with Disabilities (Equal Opportunities) Act 1995. In Denmark Disabled Peoples Organisations Denmark was formed in 1934 and has since that time worked for the rights of people with disabilities within Denmark and on an international level. In 1993 the Danish government approved the law on equality and equal treatment of disabled people compared to other citizens. This law was the first of its kind in Denmark to specifically address rights for people with disabilities. The European Parliament adopted the Resolution on the human rights of disabled people in 1995, which urges the European Union to take steps towards ensuring equal rights and opportunities for people with disabilities. In 2006 The Convention on the Rights of Persons with Disabilities was adopted by the United Nations and entered into force on May 2008. This convention establishes explicit rights for people with disabilities and is ratified by 138 nations and signed by further 158 nations (United Nations, 2013a). The overall purpose of the convention is to ensure equal enjoyments and fundamental freedom for all persons with disabilities. Regarding safety, article 11 explicitly states that protection and safety of persons with disabilities in situations of risk should be ensured (United Nations, 2006).

Another right for people with disabilities is accessibility and the demand for universal design. Buildings need to be accessible for everyone. Increased accessibility might as a consequence lead to a change in the characteristics of the building occupants. The accessibility requirements have challenged the traditional way of designing buildings and thereby highly influenced the building industry. Furthermore, the introduction of performance based building codes has entailed a larger degree of freedom in the building design. However, accessibility is not equal to egressibility. In a fire safety - and evacuation perspective, there is a lack of understanding and knowledge on the evacuation characteristics and capabilities of people with disabilities. In literature there is limited information on evacuation and evacuation characteristics for the more vulnerable segments of our population. The vulnerable segments are not limited to people with disabilities, but also include children, elderly people and people impaired by drugs and alcohol as well as people who are temporarily impaired.

The disabled segment of the population contains a large variation in impairments and consequently in experienced difficulties and needs during an evacuation. Worldwide, it is estimated that the disabled segment constitutes 10 percent of the population or 650 million people, which makes it the largest worldwide minority (United Nations, 2013b). These numbers does not include people with temporary impairments and illnesses. It is therefore of great importance to gain knowledge on how safety for this segment is ensured. The focus of this study is on blind people and people with low vision. This group is estimated to constitute 285 million people worldwide of which 39 million are blind and 246 have low vision (World Health Organization, 2013). In the United States 2% of the population of all ages is categorized as legally blind according to the American Community Survey conducted in 2011 (Erickson, Lee, & von Schrader, 2012). The survey also ascertains that the proportion of people with visual disabilities increases with age e.g. 4.1% of people ages 65-74 and 10.3% of people 75 or older have visual disabilities. Furthermore, the elderly part of society is growing these years and that creates the basis for a larger population considered visually impaired in the future.

Implementation of performance based fire safety codes allows engineers to prove a buildings safety level using computer based software tools. There exist various tools to determine the evacuation safety in a building. The tools often comprise models to predict the required safe egress time (RSET) and the available safe egress time (ASET). These models are based on research and knowledge within evacuation characteristics and behavior and fire dynamics, respectively. The models used to predict RSET is primarily based on data collected more than 30 years ago and is based on able-bodied adults. It is therefore questionable if these data describes todays building occupants accordingly. A building needs to be safe for everyone and special attention on the vulnerable segment of the population is needed. If a building is designed with the needs of vulnerable people and their characteristics in mind, it is claimed that the overall safety level is sufficient for all occupants.

There exist several commercial software tools to predict the evacuation time of a structure or building e.g. STEPS, Simulex, FDS+Evac, Pathfinder among others. These tools are able to simulate the evacuation of a building using different models. The underlying models describes varies parameters important to simulate the evacuation (Kuligowski, Peacock, & Hoskins, 2010). The models of interest for the current studies are on movement and human behavior. The software tools give us the opportunity to include knowledge on the occupants and how they react in an emergency. Applying design solutions based on prescriptive codes does not allow the engineer to include knowledge on evacuation capabilities for different segments in the population. Furthermore the complexity of the building might induce that prescriptive codes cannot be applied and performance based codes are needed. The data and results obtained through this study is intended to create the basis for further development of the used models to include knowledge on blind and visually impaired people.

1.2 Objectives

This study consists of two parts – an experimental part and an interview part. There are performed a series of evacuation exercises in an office building and afterwards the participants are interviewed about their experience with the experiment and their use of buildings in general. The aim of the evacuation experiments is to get better knowledge on the evacuation capability of blind people and people with low vision. The experiment involves analysis of video footage with respect to different evacuation parameters including walking speeds horizontally and on stairs, person densities, density dependency and flow. In addition, the behavior of the test persons and their internal interactions and their interactions with the environment will be investigated. The hypothesis to be tested in this study is if evacuation parameters for people with low vision and who are blind is sufficiently described using theories based on able-bodied people. Along this hypothesis it is tested how human behavior and interaction between evacuees influences selected evacuation parameters e.g. walking speed and walking path.

1.3 Structure of the report

This report contains and introduction, which gives the background and importance of the study. The following chapters give a description of the methodology used in the experiments and interview study. The results obtained will be presented and discussed in Chapter 3. Hereafter comes a conclusion and then the report is rounded off with a description of my personal experience conducting evacuation experiments in a foreign country and culture. The last section is included since the experiments are carried out as a part of my external research stay during my PhD at The Technical University of Denmark, Department of Civil Engineering.

2. Methodology and Data collection

2.1 Experimental Setup

The evacuation exercises are carried out in an office building situated in the Washington D.C. area. The building has six stories and is accessible for people with disabilities. There is a ramp from street level to entrance level, which is placed six steps above street level. There are revolving doors and separate doors for people in wheelchairs. The building is currently undergoing a renovation and the exercises were held in the old part of the building. The interior design of the building, in which part the exercises are held, consists of long hallways with offices and other rooms on each side. The primary vertical traffic is diverted by elevator whereas the horizontal traffic is distributed in hallways. The building is provided with emergency staircases in each corner of the building and in the middle section.

The exercises are initiated from a meeting room located on the fourth floor in one corner of the building. There is a large meeting table in the middle of the room with chairs around. The test subjects are seated around the table. The determined egress route is from the room with a right turn just after exiting the room into the hallway. The hallway is 106.5 meter long. The participants are supposed to make a left turn into another hallway after 53 meters. After 4 meters in the second hallway the participants have a fire exit to the emergency staircase on their left hand. Entering the emergency staircase the participants travel two floors of stairs to a safe place on the second floor. The stair is a two flight stair with intermediate landings. Each stair flight has ten steps and handrails in both sides. The handrail is only continuous on the inside. The building is not closed off for the experiment, and normal traffic might mix with the evacuation exercises.

The experiment is divided into five different phases, see table 1. This is done to assess how different compositions of the test group influences evacuation parameters. In the first phase the participants walked one by one and on their own through the determined emergency route. All exercises were initiated by a local warning signal. The signal was only given in the room from where the exercises where initiated in order not to disturb the normal use of the building. This first phase is considered as the reference scenario, where the participants are walking unimpeded and with their own pace and is not influenced by others. In the second phase the participants were paired two and two. It was not a requirement that the pairs should stay together, but if they felt safe doing so it was their own choice. The third phase constituted groups of three. In the fourth phase the group where split in half and in the fifth and last phase everyone was evacuating at the same time.

Table 1: Phases of the evacuation experiment.

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Single	Groups of 2	Groups of 3	Half	All

Each phase is only run one time, since the exercises where scheduled to last only one afternoon the time frame did not allowed for any replication. Prior the exercises the participants were instructed in the determined emergency route and the alarm signal. Furthermore, the order in which the participants should respond to the local alarm signal was given beforehand. The local alarm signal sounds with a time interval of 30 to 90 seconds to notify the participants.

Data from the experiments are collected by recording each phase with temporarily fixed video cameras. The video footage is afterwards analyzed and the walking speeds horizontally and on stairs, and densities are determined. Furthermore the interaction between the participants is observed and logged.

The focus of the study is the evacuation capability of blind people and people with low vision. It is likewise studied how they move individually and in groups in a simulated emergency situation.

2.2 Participants

The only requirement outlined for the participants to take part in this study is that they have low vision and is categorized as legally blind according to the American definition (Social Security Administation, 2006). Legally blindness can be translated into a visual acuity of a maximum of 20/200 measured in the best eye or having a visual field less than 20 degrees. Participants could use their usual assistive technology during the exercises no matter if it is a dog, a cane or anything else they prefer. The low vision population is limited to people who has a vision which corresponds to the American definition of legally blind. However, low vision is not only defined by the visual acuity but depends on various factors. If the current study should include a random group of people with low vision not defined by the visual acuity there would be a risk that the characteristic of the group would be too diverse. The diversity of the group is reflected in the results and if it is too diverse it would not be possible to give a proper and accurate description of the group's characteristics.

Participants are recruited from local networks, unions, and organizations with interest in safety for blind and visually impaired people. The recruitment process was initiated in August 2013. The goal was to reach around 20 participants. Unfortunately only 11 participants showed up. The age-range of the participants were from 33 years to 79 years divided on two males and nine females. Four of the participants were assisted by their guiding dogs. The physical conditions among the participants varied which can be read off the results. The degree of visual impairment is determined based on the definition given by the World Health Organization (WHO), see table 2 (World Health Organization, 2010). The system consists of six categories as shown in table 2. In table 3 the composition of the test sample are given based on gender and degree of visual impairment.

Table 2: Definition of degree of visual impairment measured in visual acuity, reproduced from (World Health Organization, 2010)

	Presenting distance visual acuity	
Category	**Worse than:**	**Equal to or better than:**
Mild or no visual impairment 0		6/18 3/10 (0.3) 20/70
Moderate visual impairment 1	6/18 3/10 (0.3) 20/70	6/60 1/10 (0.1) 20/200
Severe visual impairment 2	6/60 1/10 (0.1) 20/200	3/60 1/20 (0.05) 20/400
Blindness 3	3/60 1/20 (0.05) 20/400	1/60* 1/50 (0.02) 5/300 (20/1200)
Blindness 4	1/60* 1/50 (0.02) 5/300 (20/1200)	Light perception
Blindness 5	No light perception	
9	Undetermined or unspecified	

* Or counts fingers (CF) at 1 meter.

Table 3: Number of participants in each category of visual impairment.

Gender	Category 2	Category 3	Category 4	Category 5
Male	-	1	1	-
Female	3	1	3	2
Total	3	2	4	2

The participants were not rewarded economically for their effort due to ethical regulation. However, all participants were given a symbolic gratitude in form of a $15 gift card to Starbucks as a Thank-You appreciation. In addition, all participants were invited to dinner at a local restaurant where their experiences during the exercises were discussed and the experiment was evaluated.

Before the experiments all participants received written information about the study. In addition to the written information each participant also received a consent form, which they were asked to review. Meeting the participants before an experiment has earlier shown to be successful measured on the rate of attendance. However, in this case it was not possible to arrange meetings with participants before the experiments and contact details to the research team were made available to the participants. The participants were encouraged to contact the research team with any questions they might have. The written information gives the background for the study, procedure during the experiment, benefit for participants and society as well as sections on liability. All participants are made aware that they take part on an entirely voluntary base and are informed that they can withdraw at any time. The consent form is provided electronically, in print with plain text and with large font, and in braille. The day the experiments were carried out the participants also got oral information on the experiments. All participants were required to sign the informed consent before participation in the experiment.

2.3 Data Collection

Collection of data is done by recording the exercises with video cameras. Cameras are installed along the determined emergency route both in the corridors and in the staircase. There is used different mounting equipment based on the possible mounting options in the building. The cameras are mounted at the same day as the experiments are carried out. The mounting is completed in the morning. Chequered mats are filmed as a reference layer for the video footage in order to make measurements while extracting raw data from the recordings. The cameras used are of the type X170 Drift Innovation, manufactured by Drift Innovation, London, UK. These cameras are filming with a wide angle of 170 degrees and have a rotatable lens. The recordings are filmed with 30 frames per second which is the native format for the cameras. The cameras are placed to film from above pointing directly downwards, and with an angle. The downwards position is primarily used to determine the person density whereas the angled position gives an overview to observe the interaction between the participants and their interaction with the environment. The different positioning options in the corridor and staircase are shown in figure 1.

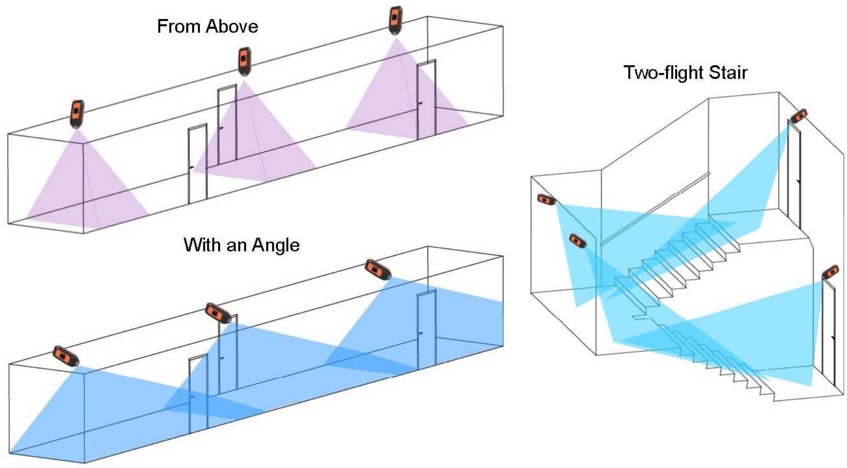


Figure 1: Camera positions

The cameras are mounted according to the plan shown in Figure 2. The floor is made of terrazzo and is provided with expansion joints for every approximately five meters. These joints are used as check points in the data analysis. The length of the corridor is 53 meters and there are 11 joints along that length. At each joint one camera is positioned filming from above and two cameras are filming with an angle pointing in opposite directions. Each phase of the experiments is recorded to separate files. Due to the internal distance between the cameras a stopwatch is used for synchronization. The synchronization process is repeated prior each phase of the experiment.

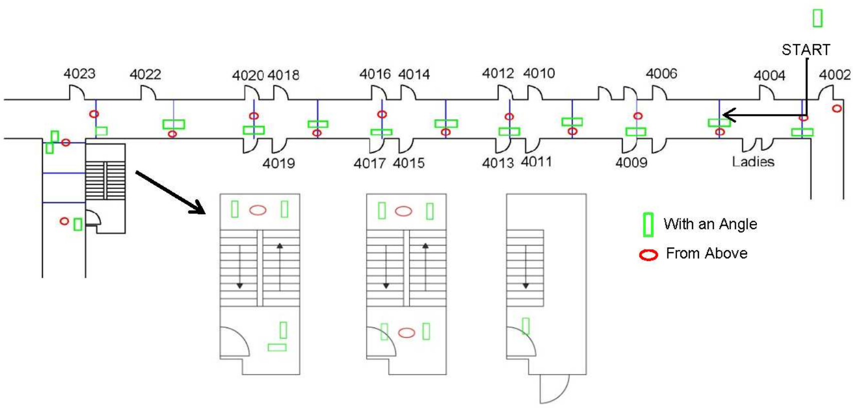


Figure 2: Initial camera plan

Movement horizontally is divided into 10 sections named A-J. The participants are registered at 11 check points in each exercise along the corridor, see figure 3. These checkpoints allow the research team to calculate the walking speed within each section. The walking speed v_h is measured as the time difference between passing two check points, Δt, divided by the length between the same two checkpoints, Δl.

$$v_h = \frac{\Delta t}{\Delta l}$$

This means that each person will be assigned a walking speed and a corresponding density for each of the 10 sections along the walking path.

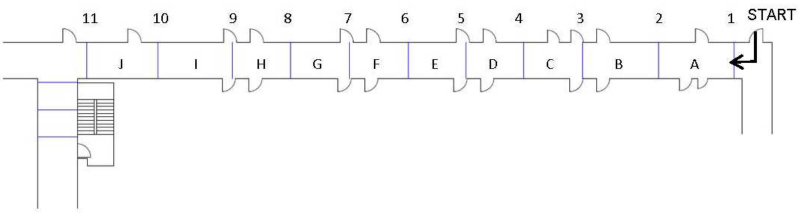


Figure 3: Division of corridor into check points and sections.

The density is measured locally each time a participant pass a check point. It is decided to use the 2 m^2-method to measure the local density. At the point in time where the participant passes the checkpoint the number of persons one meter in front of the person and one meter behind the person are counted. The width of the density area is 1 meter. In the current study some of the participants walk with their guiding dog. The dogs present during the exercises are equalized to a person in the analysis. This choice is made because a dog present during an evacuation will affect the evacuation flow and thereby other evacuees. In addition this will lead to a higher density for participants with guiding dogs while they are walking on their own.

The corridor is not without obstacles. There is a small sink installed on the wall at the fourth check point on the right hand side of the corridor. In section H there is placed a trash bin in the left hand side of the corridor, see figure 4. The obstacles are expected to influence the walking since previous studies as shown that blind and visually impaired people prefer to walk along the walls and not in the center of the corridor. The width of the corridor is 2.7 meters which allows for walking in two to three lanes.

Figure 4: Left: Obstacle on the wall. Right: Trash bin placed in the corridor

The cameras used are filming with a wide angle and to correct for the fisheye view in the data analysis a reference layer with known dimensions are used. The reference layer for the video footage is made of a chequered mat where the dimension of each square is 0.167x0.167 meters. On the mat squares of 1 m^2 is likewise marked with red tape. The mat is filmed before the exercises. During the analysis the mat is placed as a reference layer underneath the video footage. The mat is placed on the floor and the position of the participant's feet determines when they pass each checkpoint. If the feet's are not placed directly on the line for the checkpoint it is subjectively estimated when the center of gravity passes the line. This estimate is based on the weight distribution between the feet.

2.4 Interview study

The evacuation experiments were supplemented with an interview study revealing the participants experiences with the experiments. This study likewise included an assessment of their use of the public building environment including their visiting behavior of different building types and an examination of the difficulties and barriers they experienced in those buildings. This study was in addition conducted on a voluntary basis. The interview was based on a questionnaire consisting of three parts – identification, the experiment, and the public environment. The identification part involved seven questions on the age, the degree of the impairment and its origin as well as questions on assistive technologies and identification of other impairments besides their visual impairment. The second part was about the experiment and contained six questions on the participant's familiarity with the building, the difficulties they experienced, need of rest periods, assistance from others and a general evaluation of the exercises. The last part assessed the participant's use of the public environment and buildings. This part contained seven questions where each participant was asked to identify four buildings they visit. These four buildings created the foundation and were supplemented with building types from a predefined author list. The participant was thereafter asked to identify the frequency of visits, experienced difficulties, and how they orientate in those buildings. In addition the last part contained questions on the participant's awareness of emergency while visiting unfamiliar buildings.

All confidential information about the participants is kept secret to ensure their full anonymity. There is collected approval from all participants that small video recordings can be used at conference presentation and presentations of the project.

2.5 Ethical considerations

In Denmark there are two authorities to consult while performing scientific experiments involving human beings – The Danish Data Protection Agency and The National Committee on Health Research Ethics. Even though the experiments are conducted in Washington D.C., USA, the data are processed in both Denmark and the US and is a part of a Danish project, notification and approval from the Danish authorities are therefore needed.

In the case where information on the participant's health conditions is a parameter in the experiment, it is, according to the law, mandatory to notify for the Danish Data Protection Agency. In this experiment information on the participants eventually impairments is recorded and can be used for identification and it is therefore considered as a health condition. The PhD project and the activities included herein are notified to the Agency and permission to data analysis is given. Regarding The National Committee on Health Research Ethics an informal description of the project is submitted and they have judged that these experiments do not need to be notified, because they are not considered as biomedical experiments or involve humane material. It is classified as an observation, interview and questionnaire survey which are not obligated to notification (Den Nationale Videnskabsetiske komité, 2012).

Even though the project does not need approval by an ethical committee the research team at The Technical University of Denmark, Department of Civil Engineering has developed an internal codex describing ethical procedures for evacuation experiments involving vulnerable people. The internal codex prescribes that all participants in a simulated evacuation needs information about the project prior the evacuation. Dependent on the population all participants need to sign an informed consent to participate. Participant will receive both verbal and written information about the project. Participation in the experiments is on a voluntary basis and the participants are allowed to withdraw at any time. If a participant during the exercises feels uncomfortable or the like, it is possible to immediately withdraw from participation. All participants are guaranteed anonymity and none of the recorded material will be distributed to a third party.

It is expected that the participants will benefit from participation. The participants will experience how they react in a simulated evacuation, how they interact with other people around them and how the built environment affects their performance. Likewise it is expected that the experiments will benefit both science and society. The study will give scientific results that can contribute to models prescribing the evacuation behavior of people with visual impairments. The society will benefit due to an increased focus on vulnerable groups in our population and their right to be safe as everyone else.

2.6 Source of errors

Performing experiments always involves possible sources of errors. In the current study some source of errors has been detected and will be described in this section.

The experiments are recorded with video cameras, and there are several aspects about the cameras that can course errors. There are no software tools available that can be used to track the participants in the video footage and therefore the recorded material is analyzed manually. The manual analysis involves subjective judgment of the position of each participant at specific positions along the egress path. There is set up different rules for the analysis, but it is not possible to make the exact same judgment for each and every test persons. Furthermore, the participants are walking with different speeds and at different paths. Therefore their body position is not the same at all positions along the egress path. In order to reduce the error by manually analyze the recordings it is the same person and thereby the same set of eyes that has done the complete analysis. Another source of error that affects the analysis is the possible mounting options of the cameras. Since the experiments are held in a normal office building environment and not a build-for-the-purpose structure it gives challenges for the mounting of the cameras. There are several mounting options for the cameras such as suction cups, clamps, bars etc.. In the current study the 50 cameras should cover 55 meters of corridor and four flights of stairs. The building corridor was designed with smooth surfaces and it was difficult to find places to mount the cameras. Bars was stretched out between the walls, however only 12 bars were available. In some positions an open cable tray was used to fasten the cameras and then the setting of the cameras was made to fit the available bars. In the staircases existing pipes were used on entrance floors and bars were used on the intermediate landings. Regarding the staircase the lightning conditions on the intermediate landings were very poor, and that resulted in los of data because it was not possible to determine when the participants exited the stair in some cases.

Another issue to address is the realism of the situation. It can be questioned if this designed situation is similar to a real emergency. It is rarely observed that large group of blind and visually impaired people are travelling or moving together. However, it is important to gather data that can be used to make predictions on evacuation times. It is difficult to collect precise data from real incidents and experiments are therefore the closest one can get to a real incident. In addition, the alarm used in the experiments is a local alarm and not the warning/alarm installed in the building. The participants were instructed in how to perceive the alarm signal and the efficiency of the normal buildings can therefore not be measured.

The participants are walking the same egress path in five runs plus a guided tour before the experiment starts. The repeated use of the same path might lead to a training of the test persons. The training will result in an increased familiarity with the route and might result in increased walking speed. However, previous experiments performed in Sweden as evacuation from rail tunnels have not been able to capture any effect of training or learning effect due to repetition (Fridolf, Nilsson, & Frantzich, 2013). An attempt to reduce a possible training effect were to group the participants differently and ask them to walk together in their group if they felt comfortable doing so. In the results section the training effect will be discussed in relation to walking speed.

The sample of participants who took part in the exercises is committed to the society of blind and visually impaired people. They work for better living conditions and social inclusion for this segment of the population to increase equality and minimize disabilities. The participants might therefore not be a representative sample for the whole population of blind and visually impaired people. Nevertheless it is also the committed people that can be expected to be present in the building environment because they do not see their impairments as a restricting and barrier.

3. Results and discussion

The following section presents the results from the experiment and a discussion of these. The section is divided into four parts. The first part presents the results for walking horizontally; the second part gives the results for walking down stairs; the third part consists of qualitative results and observations on human behavior and interactions between participants and between the participants and the environment. The fourth part presents results from the interview concerning the participants use of different building types and the barriers they meet.

3.1 Walking horizontally

The walking speed horizontally is divided into two parts – the free unimpeded walking speed and walking speed influenced by increasing density. The limit between the free speed and the density dependent speed is set at a density of 0.54 pers/m^2.This limit is derived from previous studies conducted by Fruin, Pauls and Predtechenskii and Milinskii (Fruin, 1971), (Pauls, 1980), (Predtechenskii & Milinskii, 1978).

The data collected for the horizontal speed is collected in the corridor. The nature of the exercises and the characteristics of the participants as implied that the majority of data points are within the region of the free speed. Since four of the participants have guide dogs their density for the free speed will be 1 pers/m^2. The reason to the higher density is that a dog is counted as a person in the analysis of the evacuation flow. It is not possible to neglect the presence of the dog because it takes up space and affect the flow. Furthermore, other persons in the flow will be affected by the dog corresponding to other persons in the flow. The results for the free speed are therefore adjusted to include the results for the four persons even though the density is 1 pers/m^2.

The free walking speed is presented for the three different groups; all participants in one big group, a group encompassing participants without dogs and a group with the participants having a guide dog. These three groups are then divided into four subgroups depending on the degree of visual impairment. The division into the subgroups entail that some results are only for one person due to the small sample size of a total of 11 participants. The basis for the results is based on available data points derived from the video analysis. Table 4 gives an overview of the available data points for the different categories. It is seen in the table that there are 299 data points for the free speed at densities less than or equal to 0.54 pers/m2 without the participants with dogs. There are 169 data points for the four participants with dogs and a density of 1 pers/m^2. This gives a total amount of 468 data points for the free walking speed. In addition there are 48 data points for person densities larger than 0.54 pers/m^2, excluding the points with a density of 1 pers/m^2, corresponding to the persons walking on their own with their guide dog. There are only 4 data points for category 3 and 4 respectively and it is decided not to draw any conclusions for these two subgroups in the presentation of the density dependent walking speed.

Table 4: Data points available for walking speeds horizontally.

Group	d≤0,54 (without dogs)	d=1 (with dogs)	d>0,54 (without d=1)
All	299	169	48
Category 2 (n=3)	91	41	12
Category 3 (n=2)	74	-	4
Category 4 (n=4)	86	82	28
Category 5 (n=2)	48	46	4

The free walking speed horizontally is presented in table 5. For the first group including all participants the mean free speed is 1.23 m/s with a standard deviation of 0.48 m/s. The large deviation expresses a large variation within the group. Consulting the video footage likewise shows large variation in the participant's physical conditions. The level of fitness of the participants is not measured before the experiment and the level can therefore only be based on observations from the video footage. Comparing the mean free walking speed without regards to the degree of visual impairment, with the values prescribed by international guidelines e.g. Fire Protection Handbook (NFPA) and SFPE Handbook it is seen that it is safe to use the prescribed value of 1.19 m/s (DiNenno, 2002), (Cote, Arthur E.(Editor-in-chief), 2008). However the large variation within the sample shows that more data is needed to reduce the variation and get a statistical valid pool of data. Looking into the subgroups for all participants it is seen that the speed is decreasing as the degree of visual impairment increases except for the two persons in category 3 who has the lowest mean free walking speed of 1.06 m/s.

It is interesting to investigate what influence the use of guide dog has on the walking speed and the group is split into two parts one with the participants without dogs and another including the participants with guide dogs. The mean free walking speed for the group of participants without dogs is 1.18 m/s whereas the mean free walking speed for the group with dogs are 1.32 m/s. This indicates that the participants walking with a dog has a higher mean free walking speed compared to the participants without a dog. The interviews with the participants revealed that the participants who walked with a dog did not observe the obstacles in the egress route. The dog is trained to lead the owner around obstacles and is commanded to find e.g. the door. The dogs eyes then acts like the eyes of the owner and thereby the owner is guided around obstacles without noticing it because it is the dog that determines the walking path. There are placed obstacles in the corridor and the participants without a dog need to physical register or get in contact with the obstacle before they are able register it and then change their walking path. This circumstance can be detected as one cause for the reduced speed of the participants without a guide dog.

Investigating the subgroups for the group without dogs gives that the walking speed is decreasing from 1.72 m/s for category 2 to 0.49 m/s for category 5. The difference between category 3 and 4 is 0.02 m/s where the highest velocity of 1.08 m/s is measured for category 4. This difference in mean free walking speed between category 2 and 5 indicates that the walking speed decreases as the degree of visual impairment increases. However, it is important to state that these results only bases on a very small sample size and therefore only indicate trends that is important to keep in mind while designing buildings for all parts of the population including persons with visual impairments. The numbers found from the current experiments need validation performing additional experiments.

Table 5: Horizontal free walking speed horizontally for low densities*.

Group	Mean	Min	Max	Std. dev.
All				
All (n=11)	1,23	0,26	3,53	0,48
Category 2 (n=3)	1,50	0,40	3,53	0,52
Category 3 (n=2)	1,06	0,46	1,44	0,27
Category 4 (n=4)	1,16	0,47	2,46	0,25
Category 5 (n=2)	1,11	0,26	3,43	0,67
Without dogs				
All (n=7)	1,18	0,26	3,53	0,51
Category 2 (n=2)	1,72	1,09	3,53	0,43
Category 3 (n=2)	1,06	0,46	1,44	0,27
Category 4 (n=2)	1,08	0,74	1,89	0,20
Category 5 (n=1)	0,49	0,26	0,65	0,10
With dogs				
All (n=4)	1,32	0,40	4,43	0,40
Category 2 (n=1)	1,00	0,40	1,52	0,32
Category 4 (n=2)	1,24	0,47	2,46	0,27
Category 5 (n=1)	1,75	1,39	3,43	0,28

*Free speed is categorized as unimpeded walking speed where the density is less than or equal to 0.54 pers/m^2. A person walking alone with his/her guide dog is also having a free speed, but the density will be 1 pers/m^2 due to the presence of the dog.

The experiments also gave results for walking speed influenced by increasing person density. However, the results are only based on 48 data points mainly for participants in category 2 and 4. The available data is displayed in figure 5. The data from the experiments is displayed with the model develop by Nelson and Mowrer (N&M) (Nelson & Mowrer, 2002). The data points are supplemented with a trend line for category 2 and 4 respectively. Comparing the slopes of the trend lines with the theoretical N&M curve shows a clear difference between category 2 and 4 and the N&M model. The slope for category 2 is negative which is similar to the N&M theory. The slope is however steeper which indicate that participants in this category is more affected by an increasing density compared to able-bodied people. On the other hand the slope for category 4 is positive which is opposite to the N&M theory and the results for category 2. The positive slope for category 4 indicates that participants in this group are able to maintain and actually increase their speed with an increasing density. Since the highest density observed in the experiments is 1.33 pers/m^2, it is recommended to design further experiments where higher densities will occur. In the current experiments it was intended to create a design that forced the participants to walk closer together, but the width of the corridor allowed overtaking and the length did that the participants relatively easy could find and walk by their own pace and path. Even though the participants were asked to walk in groups of several sizes the chosen method of calculating the density did not gave rise to higher densities.

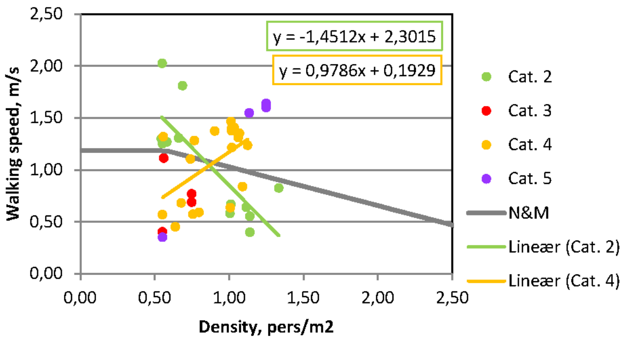
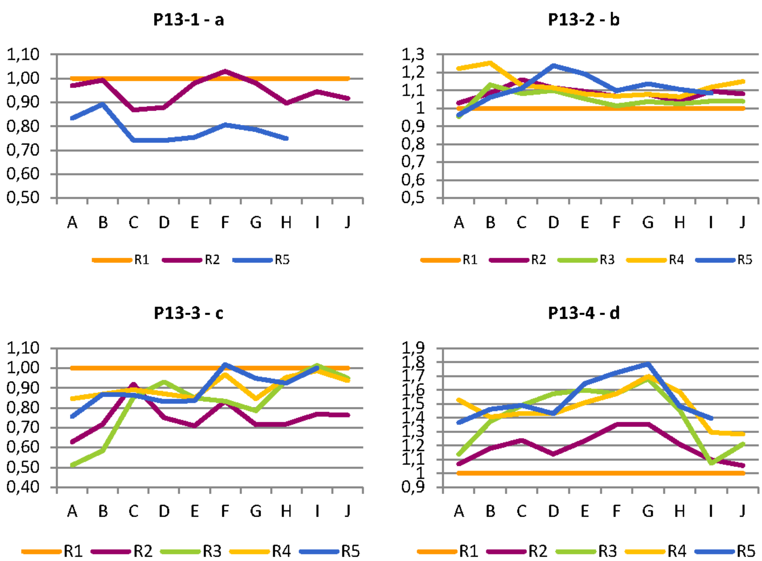


Figure 5: Person density dependent walking speed horizontally. Shown data points correspond to densities larger than 0.54 pers/m^2. Data points for persons walking on their own but with a dog are excluded.

It is of interest to investigate how the forced group formation influences the participants walking speed along the corridor. The corridor is divided into 10 sections as mentioned earlier. The walking speed is measured for each of these sections for all five runs of the experiment. To investigate the relative difference between the free walking and the walking in groups the group walking speed is normalized with the free walking speed from the first run for each of the ten sections in the corridor. This way of normalizing the walking speed results in a straight line for the first run, where the participant are walking alone and with their own pace. For the following runs it is possible to see how the walking speed is affected by the fellow participants in each run. The normalized walking speeds for each participant are summarized in figure 6 a-k (divided onto two pages).



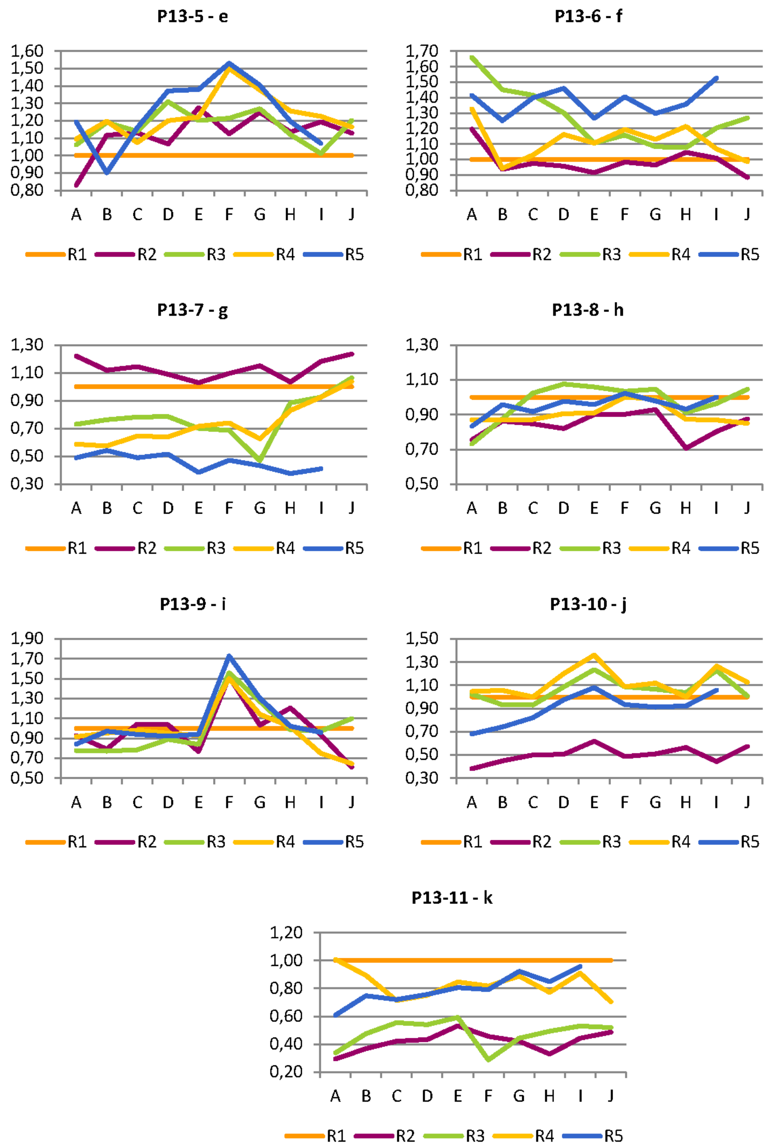


Figure 6 a-k: Normalized walking speed along corridor. Normalization is done with the free walking speed for each section in the corridor.

Normalizing in this way filter the results for the influence of the building design, but highlight how the walking speed is influenced by the other participants. From the results it is seen that some participants walking speeds are more influenced by fellow participants than others. Six of the participants maintain a walking speed within a ±10% range from their free speed when they are walking in groups compared to the majority of their runs. On the other hand other participants both reduce and increase their walking speed walking in groups with more than ±40%.The extremes are observed for P13-4 where the mean walking speed in the group configuration setup is more than 40% higher compared to free walking speed. This is a difference that indicate either that his person is pushed to walk faster in the group or that the familiarity increases with the number of runs completed. On the other hand P13-11 walks more than 40% slower in the second and third run compared to the first free speed run. This indicates that she feels a social bond within the group and reduces her speed to stay together in the group.

From figure7 it is likewise seen that the walking speed for P13-9 is 50% or more in the group runs compared to the free speed run. The reason to the peak in section F is due to a 50 % lower walking speed in this section for the free speed run. Consulting the video footage it is found that the participant changes the walking path from the right hand side to left hand side of the corridor. This shift in walking path is in the beginning of section F and explains the significant speed reduction.

In general there are observed an equal amount of runs where the walking speed is either reduced or increased with more than 20%. This demonstrates that the participants walking speed in groups are affected by other members of the group. Some participants reduce their speed while others increase their speed. The participants left the room of origin in a group but were not instructed in staying together with the group all the time. However, they were encouraged to stay together if they felt it would be natural for them individually.

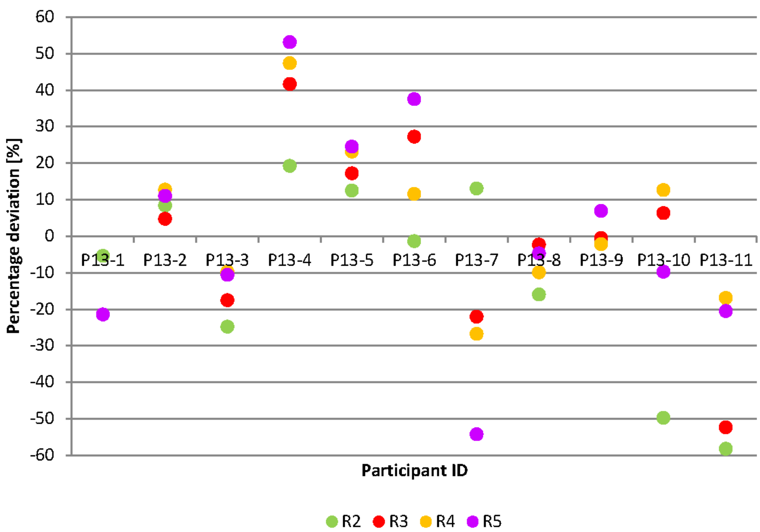


Figure 7: Percentage mean deviation from free speed for each participant.

3.2 Walking on stairs

Emergency routes often consist of both travelling horizontally and vertically. In buildings the vertical movement is often on stairs in case of emergency. For many years the public has been taught to use the stairs in case of an emergency, and not the elevator. Therefore it is of interest also to have data for movement on stairs. In the current study the participants travel down two floors in order to bring themselves to the safe place on the second floor. The two floors of stairs consist of four flights of stairs. The stairs between each floor is a two-flight stair with intermediate landings. However, due to a malfunctioning camera only data for three flights of stairs has been recorded. The walking on stairs is divided into free speed where the person densities are less than or equal to 0,54 pers/m^2 and density dependent speed where the density exceeds 0,54 pers/m^2. The participants walking with their guide dogs will experience a local density of 0,62 pers/m^2 while they are walking on their own, independent of others. The results for the participants walking with guide dog will be included in the free movement. As a consequence the data points where the participants walking alone with their dog is not included in the results for walking speed dependent on person density.

Table 6 gives an overview of the obtained data points for the free movement, free movement for the participants with guide dogs and person density dependent movement. It is seen that there in total are 140 data points for movement on stairs. These points are further divided into 76 data points for free movement excluding the participants with guide dogs, 35 data points for free movement including participants with guide dogs. The remaining 29 data points are for person density dependent movement. Since the sample is only passed on 11 participants the results will only indicate trends. It is also of interest to see how the walking speed is affected by the degree of visual impairment and there are performed a subdivision into categories of visual impairment. It is decided not to conclude anything for the categories where only a few data points are available.

Table 6: Available data points for walking speed descending stairs from the experiment for different densities.

Group	d≤0,54 (without dogs)	d=0,62 (with dog)	d>0,54 (without d=0,62)
All	76	35	29
Category 2 (n=3)	22	10	11
Category 3 (n=2)	20	0	1
Category 4 (n=4)	25	13	15
Category 5 (n=2)	9	12	2

The mean free walking speeds for the three groups (all, without dog and with dogs) are presented in table 7. If all participants are considered one group the mean free walking speed descending stairs are 0.54 m/s. The prescribed value given by international guidelines are in the range of 0.85-1.05 m/s (DiNenno, 2002), (Cote, Arthur E.(Editor-in-chief), 2008). Comparing the experimental and prescribed values show that blind and visually impaired people walk considerable slower than able-bodied people. Contrary the value prescribed in Denmark is 0.7 m/s descending stairs. The Danish value is still larger than the mean value found in the experiments. Looking at the measured minimum and maximum values it is seen that the results are in the range from 0.16 m/s to 0.92 m/s with a standard deviation of 0.21 m/s. This shows that there is a large spread within the results. Adding the spread to the mean values the result lies in the range from 0.33 m/s to 0.75 m/s. Comparing with the prescribed Danish value gives that the experimental result overlaps the Danish value. However, this is not the case with the values given in the international guide lines. The overlap between the standard deviations shows that it is not possible to give precise answers on whether the mean free walking speed found in the experiments is significantly different from the prescribed Danish value.

Looking at the subgroups with different degrees of visual impairment it is not possible to directly see any trends. The mean free walking speed for the participants in category 2 and 4 are higher than the general mean. These experiments do not confirm that the poorer the vision the lower the walking speed descending stairs. Due to the small sample size the characteristic of each individual highly affect the results. From the video recordings it is very clear that there is a large variety in movement abilities among the participants. Some participants almost run whereas others are much more careful. These behaviors will be discussed in a later section.

Comparing the results for the group with and without guide dog it is seen that the participants walking with a guide dog has a slightly higher mean free speed compared to the participants not walking with a guide dog.

The standard deviations for the two mean values are nearly the same and it is therefore not possible to determine the exact effect of the guide dog measured on the free walking speed. It is not possible to determine if there is a significant difference. The difference in degree of visual impairment in the two groups is neither possible to detect. It was expected that the walking speed would decrease the more severe the visual impairment. This hypothesis cannot be confirmed based on the experimental results in this study. In the group without dogs the participants in category 3 is slower than the participants in category 2 and 4. And in the group with guide dogs the free speed increases with the severity of the visual impairment. To confirm or deny the trends found in the experiments it is necessary to conduct further experiments. Generally speaking, the participants' affiliation and cause to participate reflect that it is people who are committed to improve the living conditions for people with disabilities. Therefore they are used to break barriers and are used to visit unknown buildings and places. It would be of high interest to conduct experiments with disabled people who are not used to visit unfamiliar places. However, recruitment of this segment of the populations is very difficult.

Table 7: Free* walking speed descending stairs for densities less than or equal to 0.54 pers/m^2.

Group	Mean	Min	Max	Std. dev.
All				
All (n=11)	0,54	0,16	0,92	0,21
Category 2 (n=3)	0,63	0,22	0,92	0,21
Category 3 (n=2)	0,36	0,16	0,62	0,15
Category 4 (n=4)	0,57	0,27	0,83	0,13
Category 5 (n=2)	0,53	0,20	0,85	0,27
Without dogs				
All (n=7)	0,52	0,16	0,92	0,21
Category 2 (n=2)	0,73	0,35	0,92	0,14
Category 3 (n=2)	0,36	0,16	0,62	0,15
Category 4 (n=2)	0,56	0,44	0,83	0,10
Category 5 (n=1)	0,23	0,20	0,26	0,02
With dogs				
All (n=4)	0,58	0,22	0,85	0,20
Category 2 (n=1)	0,39	0,22	0,64	0,15
Category 4 (n=2)	0,57	0,27	0,83	0,17
Category 5 (n=1)	0,76	0,59	0,85	0,08

* Free speeds are measured for densities less than or equal to 0.54 pers/m^2. However, for the participants walking with guide dog the density, while walking freely, is 0.62 and these values are included in the results.

The experiments also gave results for person density dependent movement downstairs. These results are displayed in figure 8 together with the theoretical model developed by Nelson and Mowrer (N&M). The N&M model is included to compare blind and visually impaired people with able-bodied people. As seen in table 6 there is only one and two data points for category 3 and 5, respectively. It is therefore decided not to include a trend line for these two categories. Generally, it is seen that the majority of data points is situated below the N&M model. The slope for the N&M model is negative giving that the walking speed decreases linearly with increasing person density. The trend lines for the experimental results for category 2 and 4 both have a positive slope indicating that the walking speed increases with increasing person density which is opposite the N&M model. The steepest positive slope is found for category 4 which imply that the participants in this group are less affected by the surrounding person density. However, it is important to notice that the highest density observed in the experiments is 0.96 pers/m^2. Results for able-bodied people gives that people can move until a density of 4 pers/m^2. It is therefore highly recommended to perform further experiments with higher person density in order to determine whether the trends found in the current study can be confirmed or denied for the high density range.

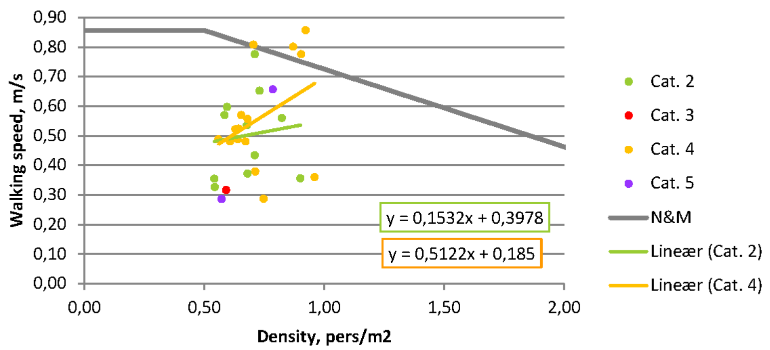


Figure 8: Person density dependent walking speed descending stairs.

3.3 Human behavior and interactions

During the experiments the human behavior and interaction among the participants were observed and registered. It was found that there was a difference in walking path for the participants with and without guide dog. The participants without dog preferred to walk in proximity of the walls whereas the participants with guide dog had a tendency to walk in the middle of the corridor. It is clear from the video recordings that there is a remarkable collaboration between the guide dog and its handler. When the participants need to turn left in the corridor to access the emergency staircase the dogs turn the corner and then the handler trust the dog that it is a correct choice and likewise turn around the corner.

As described earlier the participants were asked to walk in groups, but where not forced to it if they did not feel comfortable about it. It was seen that some participants demonstrated competitive behavior whereas others showed assistive behavior. It was not observed that the same person showed both type of behaviors. The competitive behavior was expressed by elbowing other participants to create space for him/her. Unfortunately some participants associated the fictive emergency with a competition even though they were told that it was absolutely not a competition. However, the assistive behavior was much more distinct than the competitive behavior. The assistive behavior manifests itself by participants who assist with holding doors and staying together in groups. It is seen that when the participants are asked to walk in a group, the faster test persons are turning their heads to find out where the rest of the group members are. In addition, it is seen that some of the participants voluntarily modify their walking path and walking speed to match the other members of the group.

The participants likewise communicate with each other along the egress path. In the staircases the participants with the best vision tries to explained the position of the handrail etc. to the ones with a more poor vision. The observations done during the experiments show, that there is a social force among the participants. It has not been possible to quantitatively measure the magnitude of the social force. However, it is observed and it is seen that it affect the evacuation flow. Even though the sample size is small the observed behavior shows behavioral trends that cannot be neglected in designing a buildings safety system.

3.4 Buildings and Barriers

In relation to the experiment the test persons were asked to participate in an interview survey. The interview was scheduled in the week after the experiment. The interviews were conducted with each participant individually and it was voluntary to participate. The purpose of the interview was to map what type of buildings the test persons visit in their everyday life, the frequency of visits and experienced barriers.

The interview was based on a questionnaire to give a framework and to conduct the interviews as uniform as possible. However, the participants were very enthusiastic about the questions and elaborated significantly more than expected. The interviews turned out successfully and it was interesting to receive the participants' point of view on building design for people with impairments. Ten of the eleven participants from the evacuation experiments agreed to take part in the interview session.

To design a building and its safety system it is essential to have knowledge about the building occupants. Who are they? What are their characteristics? How are they distributed in the building? All these questions and the like needs to be answered to make the right choice when designing the building and its safety systems. Nevertheless, there only exists limited information on what building types people with disabilities visit and how often. The participants in this study are therefore asked to identify four different buildings they visit. In addition, the authors had made a list with a more broad selection of building types of interest. Table 8 shows the outcome from the interview with regard to building types visited and the frequency of visits.

Looking at the results it is found that two participants identified one building present on the author list out of the four they should identify themselves. Five participants identified two buildings already listed and three participants identified three buildings on the author list out of the four. The building types solely identified by the participants appear with a star in table 8. From the same table it is seen that all ten participants identify office buildings as buildings they come in. The frequency of visits in office buildings is primarily on a daily basis for the majority of respondents, which indicate that they have a job or alike where they are sitting in an office building. The high frequency of 8 out of 10 respondents that visit office buildings on a daily basis makes it the buildings type most often visited by this test group. The second most visited buildings type on a daily basis is transport facilities. Transport facilities covers a wide range of buildings in the current study is covers metro stations, airports, and trains stations. Five out of ten uses the facilities daily, three on a weekly basis and one on a monthly basis and one do not use transport facilities at all. Residential buildings are divided into two – apartment buildings and single-family houses. The reason the separation is that evacuation is very different from those two types of buildings. For houses it is a relatively small number of persons that needs to evacuate in an emergency. On the same time there are stronger bonds in families than between neighbors in apartment buildings. In apartment buildings there are a larger number of people that needs to evacuate and they do not necessarily know each other before hand. The answers from the interview reveal that one-family houses are visited by five test persons on a weekly basis and three and two test persons on a quarterly and biannual basis respectively. Contrary, apartment buildings are only visited by one test person on a weekly basis and four, three and one test person on a monthly, quarterly and biannually basis, respectively. The frequency of visits in the two types of residential buildings shows that the test persons in this study more often visit apartment buildings compared to one-family houses. On the other hand it is not possible to conclude if blind or visually impaired people more likely visit apartment buildings than one-family houses since the building types were a part of the author list. Three of the ten respondents identified apartment buildings as one of the four buildings they should identify themselves, whereas none identified one-family houses. Nonetheless, the answers from the interviews indicate that blind and visually impaired people need to be considered in residential buildings. This study did not investigate the preferred type of housing among the test persons, since there was no question about their home.

The third and last building type that are visited on a daily basis are restaurants. Three respondents visit restaurants daily, six respondents on a weekly basis and one on a monthly basis. The high frequency of restaurant visits may partly be explained by the food culture in the US. In the US it is more common compared to Denmark to eat out for both lunch and dinner and there has been observed an increase in away-from-home food (Stewart, Blisard, & Jolliffe, 2006). Regarding evacuation in restaurants it is important that the staff is adequately educated to assist people with disabilities. People visiting a restaurant will not be expected to know exits and exit routes. People with disabilities can be challenged by the crowd around them, identify exits and may need assistance to get around chairs and tables. The barriers met in the building environment are discussed later in this section.

Shopping malls and grocery stores are most likely visited on a daily basis for most of the respondents. Grocery stores where not a part of the author list but 3 respondents identified the building type themselves. The design of shopping malls and grocery stores varies. In shopping malls there are often long hallways and a complex building layout. In grocery stores there are likewise aisles but it is more likely that the layout is logic. It was varying among the respondents if they were shopping on their own or with an assistant. In the instances where the respondents were accompanied by an assistant it would be expected that the assistant would assist during an evacuation. If the respondents were on his or her own they would rely more on assistance from staff or other customers in the store. However, it is experienced that the respondents who were shopping on their own were very independent and preferred to handle things on their own.

Assembly buildings such as theatres, concert venues and sport facilities were most frequently visited quarterly or biannually. This indicates that people with visual impairments cannot be neglected in assembly buildings, and their requirements need to be considered. A lot of things are already addressed in accessibility regulation regarding seating, toilets, stairs, entrances etc. However, special precautions should be made in relation to evacuation.

The remaining building types that only a reduced number of participants have identified are hotels, library and doctor's practice. The frequency of visits in these building types varies from weekly to annually. Hotels are identified by half of the respondents and are visited quarterly by three of the respondents. In hotels the vertical movement is often distributed via elevators; however, elevators are not to be used during evacuation. Evacuation plans are provided in each hotel room, but if you are having a visual impairment it can be very complicated to process the information given in the written evacuation plan. Some respondents have experienced oral information from the hotel staff and again others seek the information themselves. But it is important to consider the format of information that is needed for persons with a disability.

Based on the answers from the interview regarding building types and frequencies it is seen that all the chosen types of buildings are visited by the test persons. Some building types are more frequently visited than others, but it is not possible to detect a single type of buildings where you can neglect the presences of people with visual impairments.

Table 8: Identified building types and frequency of visits.

Building type	Frequency							
	Daily	Weekly	Monthly	Quarter	Biannual	Annual	Never	Total
Shopping		5	2	3				10
Transport	5	3	1				1	10
One-family house		5		3	2			10
Apartment Building		1	4	3	1			10
Theatre		1	1	5	2	1		10
Sport				1	3	1	5	10
Restaurant	3	6	1					10
Office*	8		1	1				10
Grocery*		3						3
Doctor/Medical*				1	1			2
Hotel*		1		3		1		5
Library*			1	1				2

Now the building types has been identified the next question that is interesting is what kind of barriers the respondents meet, when they navigate in the building environment. The results are given in table 9. Besides the detected barrier the answering rate is given. The barriers are grouped into barriers in buildings, informational barriers, obstacles and vertical movement.

In buildings the respondents have identified different barriers. The most common barrier is an unpredictable layout of the building. Examples of an unpredictable layout could be one-two steps in the middle of a corridor or changing width of corridors. Blind and visually impaired people need a logical layout giving them the sense of knowing where to go. Another barrier that the respondents meet is poor lightning conditions. This parameter is especially important for the respondents who have low vision. This group of people uses their sight as much as they can. If the lightning is poor they have difficulties in identify and read signs, finding specific things etc.. The people with low vision would highly benefit from good lightning conditions, but also able-bodied people would benefit from a light and bright building environment. An example is the stair case in which the experiments were held. The lightning was very bad and the participants had difficulties in distinguish the edge of the landing with the treads.

Open spaces are likewise a barrier for the interviewed participants. It is difficult for this segment of the population to navigate in an open space where it is difficult to know the layout. It is seen from the experiments that blind and visually impaired people are more likely to walk in close proximity of the wall in a corridor with exception of the ones who are assisted by a guide dog. It was found that the dog is able to guide and navigate the handler around an obstacle. Three of the ten respondents found it difficult to navigate in the open space. Four of the respondents were assisted by a dog and did therefore not mention the open space as a barrier. The same answering rate of three persons out of ten was found for shinny surfaces and doors. A shinny surface can reflect disturbing light to the surroundings. Reflected light can dazzle people in the building and make navigation and orientation in the building difficult. The barriers concerning doors consist of finding them and figure out where they lead to.

The last barrier in buildings that is identified is related to choice of materials and colors. Specifically, in the experiment the participants criticized the uniform choice of materials for doors and walls. This segment of the population often uses their hands when navigating in a building and in the current building the surface of the wall and the exit door was very much alike. Therefore it was difficult for the participants to determine whether the door to the staircase was an emergency exit door or just a normal door. In addition, marking on the floor in front of the exit would ease the recognition of an emergency exit. In the interview the respondents identify carpets as difficult to move on and also geometrical patterns on the floor makes it difficult to orientate. It was suggested to have different textures on walls and emergency doors and differences in normal doors and emergency doors. Likewise differences in color could be valuable to recognize different functions in the building.

The second group of barriers consists of informational barriers. The main barrier identified was position of signage and if signage was available. Some of the respondents claimed that it is not possible for people with low vision to navigate via signs if these are placed up to high. In some of the interviews the position of emergency exit signs above the door was discussed. It was suggested that the signs should be positioned at eye level. There are both for and against signs at eye level; firstly it can be difficult to locate a sign at eye level if the place is very crowded, secondly it might be difficult to locate and identify the sign on a distance. However, in a smoke filled environment the sign will still be readable if it is positioned at eye level. The second barrier is the format of the information. Blind people and people with low vision experience difficulties in processing normal written information. The respondents requested raised letters and numbers, which would make it easy for this group to process the information. Likewise information in braille is suggested. The last informational barrier is information systems. The respondents pinpoint that a broken information system e.g. broken loud speakers, is a barrier to get the information to the relevant persons in question. Another issue is the loudness of a possible warning or alarm system. Blind and visually impaired people use their hearing during navigation; they are actually able to determine whether a door is open or not when they pass it. Therefore a very loud alarm will reduce the possibility to use the hearing during navigation in the building. On the other hand if the alarm is not loud enough other building occupants will not pay attention to it and respond to it. The loudness of alarm is a very good example of an issue where different segments of the population have different requirements. In a buildings safety design compromises are need to satisfy all segments of the building occupants.

Obstacles are in addition identified as a barrier. However, obstacles can take many designs. Specifically furniture constituted a barrier for the respondents but also other people or traffic was identified as a barrier. Furniture placed in an illogical way or placed where it is not used to be creates a barrier, because the blind or low vision person tries to visualize and remember how a room looks like. If the design then changes they do not have a chance to know it unless somebody tells them. Regarding people being an obstacle is based on their presence in a pedestrian flow. As blind or visually impaired you are not able to register people around you in the same way as normal-sighted people. People without visual impairment are able to use their sight to adjust walking speed and path based on other people around them. This is not possible in the same way for people with visual impairments. One example could be a blind man with his mobility cane walking on the street. He approaches a pedestrian crossing where people are queuing due to red light. As he gets closer he hit some of the other people around him, but suddenly they are gone because the light has turned green. It is then difficult for the man to determine whether the thing he hit was a permanent fixed obstacles or another person what was just a temporary obstacles that disappears as fast as it came.

The last group of barriers is identified in relation to vertical movement. The respondents experience barriers when using stairs. It was mentioned that the presence of handrails are essential and that the handrails are continuing on landings. In addition, the handrails should start before the first tread. Otherwise the blind or visually impaired person can fall down the stairs in the attempt to find the handrail. Another issue about stairs is marking of the edge of each tread. If the tread are not marked it is difficult for a blind or visual impaired person to distinguish the tread from the normal floor. Likewise difference in texture on steps and normal floor is suggested. Seven of the ten respondents indicated that stairs constituted barriers for them in the building environment. In buildings higher than one floor stairs always is a part of the egress path. Therefore it is important that they are designed in an adequate way. It is observed that this segment of the population is very dependent on the handrail when moving on stairs.

Five respondents have indicated that escalators are a barrier. The barriers detected regarding escalators are the width of it. The width is primarily an issue for the respondents with guide dog. When a blind or visually impaired person is walking with his/her dog the dog will often walk side by side with the handler. If the escalator is too narrow there will not be enough space for the dog. Another problem for the persons with guide dog is the risk for the dog to get their paws and fur stuck between the lamellas on the moving treads. Likewise it can be difficult for the blind or visually impaired person to locate the escalator. However, these people are used to ask how to find this and that and rely on assistance from people around them.

The third way of moving vertically is by elevator. In addition, the elevator is identified as a barrier. The main problem with the elevator is the buttons. The respondents has experienced that the information on the buttons were not in an accessible format and therefore they could not press the right one. The respondents request raised letters or braille on the buttons to identify which floor corresponds to which button.

Common for the barriers the respondents have identified in the building environment is that the requested changes also would benefit able-bodied adults. It is claimed that if a building is designed with a universal and accessible design in mind many segments of the population will benefit from it. The universal and accessible design should be implemented early in new building projects. If it is implemented after the building is built it becomes much more expensive.

Table 9: Identified barrier and answering rate for each barrier.

Barrier	Answering rate
Building	
Unpredictable layout	8
Lightning conditions	5
Open space	3
Shinny surfaces (glare)	3
Doors	3
Choice of material and color	2
Information	
Position of / available signage	6
Format	4
Systems	3
Obstacles	
Unexpected	5
Furniture	3
People / Traffic	3
Vertical Movement	
Stairs	7
Escalator	5
Elevator	5

4. Conclusion

The current study investigated the evacuation characteristics and capabilities of blind and visually impaired people. The results found are based on a series of evacuation exercises held in an office building in Washington D.C., USA. The exercises were performed in September 2013 as a part of the authors research stay in Boston, MA, USA.

It was found that the free walking speed horizontally is comparable to values found in international guidelines. There is likewise observed a difference in the free walking speed for people with and without guide dog. The trend was that the participants with a guide dog had a higher free walking speed compared to the participants. Even though the free speed horizontally is comparable to literature the standard deviation is large, which indicate that more data are needed to validate the result. The effect of an increasing density was also studied. It was found that the degree of visual impairment was essential. The participants positioned in category 2 was highly affected by the increase in density and the slope of the trend line was steeper compared to the N&M model. Contrary the participants in category 4 were able to maintain and increase their walking speed even though the density was increasing. However, only a limited set of data was available and the results only indicate trends.

Stairs was also a part of the egress path and the mean free walking speed descending stairs was found to 0.54 m/s for the whole group. There is found variations in the free walking speed descending stairs dependent on degree of visual impairment and the presence of a guide dog. The standard deviations are however overlapping each other and it is not possible to conclude if the difference is significant. Regarding influence of increasing density it is found that the majority of data points are situated below the N&M model and therefore the N&M can be considered on the non-conservative side. However, the amount of data is highly limited.

The behavior and interaction among the participants where likewise studied. It was found that some participants had an assistive behavior where they were holding doors for each other and adjusted their walking speed to other members of their group. Contrary, assistive behavior was also observed for some of the participants. None of the participants showed both assistive and competitive behavior.

The participants were also interviewed about what building types they visit and the frequency of visits. It was found that the most visited building type was office buildings, but also restaurants and transport facilities were visited by the majority of the respondents. In relation to the buildings environment the participants were asked to identify barriers they meet. The most dominant barrier was the building layout which made it difficult for the respondents to navigate. Also signage, lightning and stairs were identified as barriers. During the interviews suggestions to possible solutions were also presented and discussed.

The results from this study shows, that the evacuation characteristic of blind and visually impaired people is not completely comparable to able-bodied adults. It is therefore important that fire safety engineers are aware of the parameters where a difference is found in order to ensure a sufficient safety level.

4.1 Outlook

The results revealed from the current study indicate trends regarding evacuation characteristics. Since the data are limited the author recommends conducting similar experiments to validate the already found results. Although the results only indicate trends people in different interest organization are very interested in the outcome from the study. The author has experienced an increasing interest in the topic among people with a special interest in living conditions and civil rights for people with disabilities. Furthermore, there is an increased focus on this segment of the population.

The author expect that the results can influence future guidelines on the topic of evacuation and underlying scientific documentation can be used as input parameters in safety design of buildings.

Furthermore, the author is participating in regulatory work under the International Organization for Standardization (ISO). The work consists of expert statements about guidelines for design of evacuation experiments and selection of design occupant behavioral scenarios and design behavior. The work is conducted within in the working group 11 under ISO/TC 92/SC 4. In addition the Low Vision Design Committee of the National Institute of Building Sciences in Washington DC, USA, is very interest in the outcome and wants to use the results as a reference in their work.

In order to increase the knowledge on evacuation characteristics of the studied segment of the population and thereby increase their safety it is suggested that future research should cover the following:

- Conducting experiments with a larger sample sizes to get statistical valid data.
- Investigate correlations between physical fitness, age, degree of visual impairment and walking speed.
- Conduction experiments giving results in the high density area to confirm or denied the trends observed in the current and previous studies.
- Investigate the influence of a guide dog for the handler, for the evacuees around the handler and the evacuation flow in general.
- Conducting full scale building evacuation experiments with heterogeneous groups to study the interaction between able-bodied people and blind and visually impaired people.
- Broaden the data collection via similar experiments for other types of impairments with the same areas in focus.
- Test different building layouts and configurations to assess how barriers for this segment of the population can be minimized.

Acknowledgement

The author is very thankful to Østifterne who has funded the project and the external research stay without their contribution is has not been possible to conduct the experiments. In addition, the experiments would not have become a success without a great job done by Robert Solomon, National Fire Protection Association, who organized the building where the experiments were held and Marsha Mazz, US Access Board, who assisted in the recruitment process. Also thanks to Allan Fraser and Rita Fahy from National Fire Protection Association who assisted in preparing and reviewing information and consent form to the participants. Furthermore, the author is grateful for the input and supervision giving by Anne Dederichs who is always enthusiastic about the process and results and very good at keeping the motivation on a high level.

Finally, the author would like to express a great thanks to all the participants, who took part in the experiments and took their time to perform the experiments and participate in a subsequent interview. Without their valuable contribution there have not been any experiments.

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Appendix L

Experimental Plan - RESC

Type	Experimental Plan
Title:	**Experimental Plan - RESC**
Author:	J.G. Sørensen
Year:	2012

DTU Civil Engineering

TrygFonden

EUROPEISKA UNIONEN
Europeiska regionala utvecklingsfonden

Interreg IVA
ÖRESUND – KATTEGAT – SKAGERRAK

DTU

Experimental Plan for Tunnel Evacuation of mixed populations

September 3, 2012

Introduction

Tunnels, high-rise buildings, shopping centers and similar buildings and structures are categorized as complex buildings or structures. The term complex buildings or structures arises because these types of constructions entails an alternative thinking in solving problems concerning the use on a daily basis and in case of emergencies.

Concerning the fire safety of complex buildings and structures considerations on the evacuation procedure, number of staircases, use of elevator, total evacuation times design of egress path etc. should be made. The design of such constructions is considered as a prototype and it is not possible to use the prescriptive codes with requirements on e.g. distance to nearest exit, width of exits and compartment size, and the performance-based codes should be applied.

With the introduction of the performance-based fire safety codes the safety level in buildings and structures can be proven applying fire safety engineering methods (Hadjisophocleous, Benichou, & Tamim, 1998). The calculations need to show that an adequate safety level is obtained within the building. The calculations consist of both evaluation of the time until critical conditions occur (the available safe egress time - ASET) and the time it takes until everybody in the building has evacuated to a safe place (the required safe egress time - RSET). The background theory for the evacuation calculations is primarily based on the evacuation characteristics of able-bodied people. However, studies have shown that the more vulnerable part of the population such as children, elderly people and people with disabilities are more likely to suffer during an emergency (Manley, Kim, Christensen, & Chen, 2011). It is therefore important to consider these parts of the population in the fire safety design.

There has been an increasing focus on the accessibility to buildings during the last decades. This implies that people with e.g. an impairment are able to enter buildings and use the facilities in different types of buildings. On the other hand the increasing focus on accessibility and good barrier-free design is not the assurance for egressibility (Papaioannou, 2006). This is an additional fact that makes it important to include the vulnerable part of the population in fire safety design of buildings.

Objectives

The aim of the experiments is to get better knowledge on the evacuation capability of a mixed population from a train inside a tunnel. The composition of the participants represents the statistical composition of the Danish population. The experiments comprise investigations on the walking speeds horizontally and travelling on stairs, human behavior and the interaction between participants. The interactions between participants are defined as verbal interaction through guiding and instructions and physical interaction where people are physically assisting each other during the exercise. The social relation between the participants is likewise considered as a parameter for the interaction. In addition the evacuation flow through sections of the egress path, with different designs or layouts, is evaluated to see if the design or layout matters or has an influence on the flow.

Experimental Setup

The evacuation experiments are carried out in a tunnel section similar to The Great Belt Tunnel located at Rednings- og SikkerhedsCenter, Korsør. The tunnel section is provided with a rail track and an IC3-train. The train is similar to the ones DSB uses daily in The Great Belt Tunnel. One part of the train is furnished with seats and tables as the trains in daily use. This part has 23 seats where 3 of them are folding-seats. One exit leads from this part of the train to the concrete platform in the tunnel (a drawing of the train is placed in a following section). The other part of the train is damaged and is only used for training firefighters. This part is not considered or used throughout the experiments.

The test tunnel is 60 meter long and is provided with two cross-tunnels with an internal distance of 40 meters. The participants are instructed to use the nearest cross-tunnel placed approximately 4 meters form the train exit. The cross tunnels lead the participants to the outside of the tunnel. In The Great Belt Tunnel the cross tunnels connect the two railway pipes. In case of fire in one pipe the opposite pipe is considered as a safe place. In the current experiment the outside of the tunnel is considered a safe place and the exercise is aborted when all participants have reached outside. The experiment is divided into 4 different setups. The difference between the setups is the composition of the test population. The four setups are show in Table 1.

Table 1: Test population for the four setups.

Setup 1	Setup 2	Setup 3	Setup 4
Without mobility impaired	Without visual impaired	Without Children	Able-bodied people

Each setup runs 5 times with the same test population for a period of approximately 45 minutes. A small break between each setup is scheduled to instruct the next group of people (schedule of the day is showed in one of the following sections) and reset camera equipment. The base for the composition of the first three setups is the statistical composition of the Danish population. However in each setup a specific group of impaired people/ group of the population is left out to see how their presence affects the evacuation times and flow. In setup 1 the test population corresponds to a statistical composition of the Danish population with the exception of mobility impaired people[1]. The mobility impaired people are not represented in this setup to see if the evacuation times and walking speeds are affected by their presences. Setup 2 have the same composition as number 1 but the blind or visually impaired people are replaced with mainly able-bodied people but also people with mobility impairments who's impairments originates from either illness or accident. The composition of the first setup is also the base for setup 3, however all children are replaced with visually impaired participants supplemented with able-bodied people and mobility impaired people. The last setup is number 4, which only comprises able-bodied people. The results from this setup constitute the reference for the other setups and are used for comparison.

Data from the experiments are collected by recording each experiment with temporarily fixed video cameras. The videos are afterwards analyzed and the walking speeds horizontally and on stairs, densities and flow through doors are determined.

[1] In Denmark the definition of being mobility impaired is floating and it is difficult to assign the most representative description of the impairment. For instance an elderly person who have difficulties in walking and have reduced eyesight. The question is then, if this person is just an elderly person, a mobility impaired person or a visually impaired person (Socialstyrelsen, 2012).

The focus of the study is the evacuation capability of a mixed population. The participant's are therefore not exposed to conditions that can appear during fire e.g. smoke, heat, flames etc.

Participants

The composition of the participants is made on the basis of the statistical representative composition of the population in Denmark. This ensures that the population used in the experiments reflects the demography in Denmark and can be categorized as heterogeneous. This wide range of people results in a comprehensive recruiting where relevant organizations and/or institutions are contacted. Recruiting of people is started in the beginning of December 2011. Table 2 gives an overview of the number of people to recruit and the distribution. Possible places to recruit the participants from are likewise given as well as the color of the group. The purpose of the color is described later.

Table 2: Distribution of participants

Type of section	Number of participants	Danish Population[2]	Possible recruiting option	Cap Color
Able-bodied people (A)	48	64%	DSB, Hjemmeværnet, Jobcenter, Sund og Bælt A/S, Slagelse Kommune, Sygeplejeskolen Slagelse, Facebook	Surf Blue
Children (<14) (C)	25	18%	Local commune school	Lime Green
Elderly People (>65) (E)	12	18%	Aktivitetscenter Teglværksparken,	Fuchsia
Visually impaired people (V)	2	1,2%	Dansk Blindesamfund	Non
Hearing impaired people[3] (H)	3	5%	Danske Døves Landsforening	Yellow
Cognitive impaired people (K)	4	4,2%	Facebook, Interest organizations	Kelly Green
Mobility impaired people (M)	3	4,5%	Korsør Handicap Idræt, Facebook, Spastikkerforeningen	Non

The participants will be paid by presents and can freely choose between four options (Gift vouchers for dinner, books, cinema or toys) each having a value of 200 DKK. Furthermore they will have their travel cost covered. The participants are carefully informed that participation is at one´s own risk. DTU do not have an insurance that covers the participants in case of an incident.

All participants are given written information about the project before they assign for the experiments. Large information meetings are arranged at different recruiting locations. At these meetings the possible participant's have the opportunity to ask all questions they might have and they can likewise sign up for participating in the experiments. The content of the larger information meetings is to give overall information of the project (a summary of the written information) but the main focus will be more on practical things about the experiments. In addition individual meetings with as many as the participants as possible will be held and the format of these meetings is; first the written information will be ex-

[2] The sum of the percentages below is more than 100 because the impairments are a part of A, C and E. The sum for A, C and E equals 100%.

[3] In this project a person is categorized as hearing impaired if hearing aid is needed, this includes people who are deaf and have severe hearing loss.

plained further and afterwards the focus will be on the questions the participant might have. At the end of these meeting the participants are asked to sign the informed consent. On the day of the experiments the most important parts from the written information and the informed consent will be repeated.

Procedure

The participants are recruited in the period from December 2011 to ultimo April 2012. In the same period individual and larger information meetings will be held.

The experiments are carried out on the 15th of May, 2012 and the program of the day is given below.

Program for the day

09:15-09:45	Arrival and registration of the participants. Collection of completed informed consents (if someone has forgotten the consent some copies are brought.)	
09:45-10:15	Introduction and information on the experiments and the project.	
10:15-11:00	Setup 1	
11:00-11:15	Pause	10.30-11.30 Elementary Firefighting Group 1
11:15-12:00	Setup 2	
12:30-13:15	Lunch, Group 2	11.45-12.30 Lunch, Group 1
13:15-14:00	Setup 3	
14:00-14:15	Pause	13.00-14.00 Elementary Firefighting Group 2
14:15-15:00	Setup 4	
15:00-15:30	Evaluation of the exercises and thank you for the participation	

When the participants are arriving at the test location they are registered and receive a bag with a cap in a specific color, participation number and safety pins for fastening, individual programs and a ball pen. For the children there is also a small booklet with some exercises concerning fire. The cap represents the color of the particular section of population. The numbers are to be placed on the front and fasten with the safety pins. The color and numbers are used to ease the recognition of the participants on the recorded videos.

All the participants are given a small introduction to the following experiments and the procedure is explained. The first group is guided to the tunnel and is instructed in the procedure of the experiments. Meanwhile the waiting participants are given a lecture in elementary firefighting.

The participants cannot stay in the same area as the test facility and therefore a waiting area is established in connection to the building where the registration and information are given and the lunch is served. The waiting area is located approximately 5 minutes walk from the test tunnel with other buildings in between. The communication between the waiting area and the tunnel is therefore carried out using walkie-talkies. Four teams are assigned different tasks during the day. The tasks for the different teams are described in a later subsection. After the first two setups lunch is served. After lunch the last two setups are run. The day is finished with a short evaluation.

Data Collection

Collection of data is done by recording all the exercises on video. Cameras are installed inside the train and in the escape route. Installation of the cameras is temporary and will not leave any marks on the train or tunnel. Different mounting equipment will be used. The cameras are mounted at the location the day before the experiments. The cameras are placed to film both direct downwards, and from an angle. The downwards position is primarily for determining the person density whereas the angled position gives an overview to observe the interaction between participants. The preliminary position of the cameras is sketched in Figure 1.

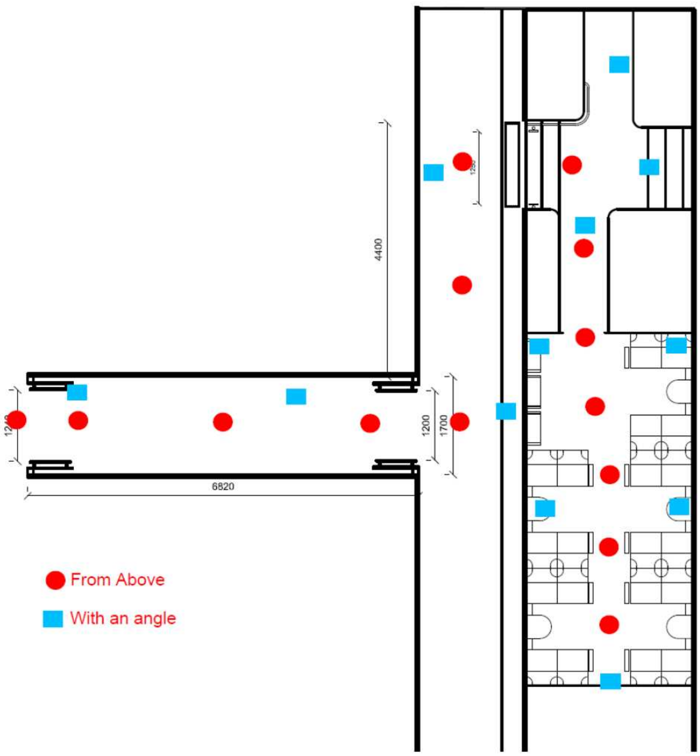

Figure 1: Preliminary camera plan.

The actual placement depends on the mounting options at the location. Before the experiment starts a squared mat is filmed. The squared mat is used while determining the person density and the walking speeds. Testing of battery lifetime has showed that a single set of batteries for each camera is not sufficient. The batteries should therefore be replaced during the experiments. However it is not possible to demount each camera, replace the batteries and mount the camera in the exact same place, and this is also very time consuming and there is no space for that in the schedule. The solution is to place two cameras at each place marked on figure 1 and then use the first set of cameras before lunch (odd camera number) and the second set after lunch (even number). This implies that the mat should be filmed twice; one time for the first set of cameras, and one time for the second set of cameras. For the first set the mat is filmed before the exercise and for the second set the mat is filmed after the exercise. The cameras are not able to record all exercises and store it in one file. Therefore the mat and each exercise are addressed to different files. In order to do this, the cameras are tuned into standby mode between each exercise by use of a remote control.

Positioning of the participants inside the train is done in a random order within each setup. The composition within each setup is the same but the actual position varies throughout the runs.

Parallel to the evacuation exercises some participants are asked to take part in an interview regarding their experience with the actual experiment. Beyond this the interview aims at clarify the experiences the participants have visiting other buildings both traditional and complex. The target group is the elderly people and those with impairments. The interviews are conducted on the basis of a questionnaire and are recorded with a dictaphone. The duration of each interview is estimated to 10-25 minutes.

Tasks on the day of experiments

There are three places at the test location to be manned;

- Waiting Area (3 persons)
- Interview Area (1 persons)
- Tunnel (5 persons)

The tasks for the different places are;

Waiting Area	- Registration of participants at arrival
	- Handing out start-up bags and gifts
	- Answering questions from the participants
	- Responsible for the meals
	- Preparing the next group and on signal send them to the tunnel
	- Guiding participant who are not active in the tunnel during morning or after lunch to the place of elementary firefighting
	- Practical assistance primarily for the elderly and people with impairments
	- Keep non-active participants away from the tunnel area
Interview Area	- Interviews the elderly people and those with impairments
	- Record each interview to its own file
Tunnel	- Briefs the participants on the experiments
	- Assign seats/positions
	- Prepare cameras
	- Observe during the experiments
	- One have the responsible for starting the exercises

The waiting area and the tunnel is placed approximately 5 minutes walk from each other and the communication between the two areas are done with walkie-talkies.

Each assistant receives a portfolio with the following information regarding the experiment;
Time schedule of the day, map of the location, possible questions with corresponding answers, description of the different tasks (each assistant should be able to manage all task in case of illness), a list of the participants, numbering of seats in the train, placement of category for each run in the setups, observation schemes for each setup, telephone list and a salary form. In addition to this each assistant should be wearing a yellow safety west.

Ethical considerations

In Denmark there are two authorities to consult while performing scientific experiments involving human beings – The Danish Data Protection Agency and The National Committee on Health Research Ethics.

In the case where information on the participant's health conditions is a parameter in the experiment, it is, according to the law, mandatory to notify for the Danish Data Protection Agency. In this experiment information on the participants eventually impairments is recorded and can be used for identification and it is therefore considered as a health condition. The project is notified to the Agency and permission to data analysis is given. Regarding The National Committee on Health Research Ethics there is send an informal description of the experiments and they have judged that these experiments do not need to be notified, because they are not considered as biomedical experiments or involve humane material. It is assessed as an observation, interview and questionnaire survey which are not obligated to notify (Den Nationale Videnskabsetiske komité, 2012).

Before the participants are allowed to take part in the experiments they need to fill in an informed consent. Three different informed consents are available; dependent on which population the participants belong to: one for the children, one for the adults and one for adults who are not able to sign themselves. In addition, everybody receive verbal information before the experiments starts. Participation in the experiments is on a volunteer basis and the participants are allowed to withdraw at any time. If a participant during the exercise feels uncomfortable or the like it is possible to withdraw from participation. The signal to withdraw during an exercise is to contact one of the assistants in the yellow safety west verbally or physically by waving with the hands.

Benefits for the participants are that they get a better knowledge on their own evacuation capability in a situation with many people; they can test how they react in a simulated emergency situation. They contribute to an increased amount of data for heterogeneous populations in an evacuation situation.

Acknowledgement

The project is a part of the large Interreg IV A project between Lund University and Technical University of Denmark. The project is entitled *"KESØ"* and is funded by the European Union. These experiments are partially funded by EU. The other part is funded by Trygfonden, Denmark.

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Appendix M

Experimental Plan - WDC

Type	Experimental Plan
Title:	**Experimental Plan - WDC**
Author:	J.G. Sørensen
Year:	2013

DTU Civil Engineering

Experimental Plan for Evacuation exercises involving blind and low vision people

November 21, 2013

Introduction

Throughout the last decades there has been an increasing focus on human and civil rights for people with disabilities. Nevertheless, the history of human rights can be dated back to 539 B.C. with the Cyrus Cylinder, but it was first in 1948 with the adoption of The Universal Declaration of Human Rights that human rights were assembled and codified into one single document. One of the first initiatives for specific human rights for people with disabilities was undertaken in the United States of America. In 1990 the Americans with Disability Act were signed into law, and are the most comprehensive pieces of legislation in the United States that prohibits discrimination of people with disabilities and give them the opportunity to live a mainstream American life. Australia passed on their Disability Discrimination Act 1992 in 1992, which provides protection for everyone against discrimination based on disability. This act encompasses the individual person who is treated unfairly due to a disability but also the person's relatives, friends, carers, co-workers or associates. In United Kingdom a similar Disability Discrimination Act was passed on in 1995. In the same year India adopted their Persons with Disabilities (Equal Opportunities) Act 1995. In Denmark Disabled Peoples Organisations Denmark was formed in 1934 and has since that time worked for the rights of people with disabilities within Denmark and on an international level. In 1993 the Danish government approved the law on equality and equal treatment of disabled people compared to other citizens. This law was the first of its kind in Denmark to specifically address rights for people with disabilities. The European Parliament adopted the Resolution on the human rights of disabled people in 1995, which urges the European Union to take steps towards ensure equal rights and opportunities for people with disabilities. In 2006 The Convention on the Rights of Persons with Disabilities was adopted by the United Nations and entered into force on May 2008. This convention establishes explicit rights for people with disabilities and is ratified by 138 nations and signed by further 158 nations (United Nations, 2013a). The overall purpose of the convention is to ensure equal enjoyments and fundamental freedom for all persons with disabilities. Regarding safety article 11 explicitly states that protection and safety of persons with disabilities in situations of risk should be ensured (United Nations, 2006).

Another right for people with disabilities is accessibility and the demand for universal design. Buildings need to be accessible for everyone. Increased accessibility might as a consequence lead to a change in the characteristics of the building occupants. The accessibility requirements have challenged the traditional way of designing buildings and thereby highly influence the building industry. Furthermore, the introduction of performance based building codes has entailed a larger degree of freedom in the building design. However, accessibility is not equal to egressibility. In a fire safety - and evacuation perspective there is a lack of understanding and knowledge on the evacuation characteristics and capabilities of people with disabilities. In literature there is limited information on evacuation and evacuation characteristics for the more vulnerable segment of our population. The vulnerable segment is not limited to people with disabilities, but also include children, elderly people and people impaired by drugs and alcohol as well as people who are temporarily impaired.

The disabled segment of the population contains a large variation in impairments and consequently in experienced difficulties and needs during an evacuation. Worldwide, it is estimated that the disabled segment constitutes 10 percent of the population or 650 million people, which makes it the largest worldwide minority (United Nations, 2013b). These numbers does not include people with temporary impairments and illnesses. It is therefore of great importance to gain knowledge on how safety for this segment is ensured. The focus of this study is on blind people and people with low vision. This group is estimated to constitute 285 million people worldwide of which 39 million are blind and 246 have low vision (World Health Organization, 2013). In the United States 2% of the population of all ages is categorized as legally blind according to the American Community Survey conducted in 2011 (Erickson, Lee, & von Schrader, 2012). The survey also ascertains that the proportion of people with visual disabilities increases with age e.g. 4.1% of people ages 65-74 and 10.3% of people 75 or older have visual disabilities.

Implementation of performance based fire safety codes allows engineers to prove a buildings safety level using computer based software tools. There exist various tools to determine the evacuation safety in a building. The tools often comprise models to predict the required safe egress time (RSET) and the available safe egress time (ASET). These models are based on research and knowledge within evacuation characteristics and behavior and fire dynamics, respectively. The models used to predict RSET is primarily based on data collected more than 30 years ago and is based on able-bodied adults. It is therefore questionable if these data describes todays building occupants accordingly. A building needs to be safe for everyone and special attention on the vulnerable segment of the population is needed. If a building is design with the needs of vulnerable people and their characteristics in mind, it is claimed that the overall safety level is sufficient for all occupants.

Objectives

The aim of the experiments is to get better knowledge on the evacuation capability of blind people and people with low vision. The experiment involve analysis of video footage with respect to different evacuation parameters including walking speeds horizontally and on stairs, person densities, density dependency and flow. In addition, the behavior of the test persons and their internal interactions and their interactions with the environment will be investigated. The hypothesis to be tested in this study is if evacuation parameters for people with low vision and who are blind is sufficiently described using theories based on able-bodied people. Along this hypothesis is it tested how human behavior and interaction between evacuees influences selected evacuation parameters e.g. walking speed and walking path.

Experimental Setup

The evacuation exercises are carried out in an office building situated in the Washington D.C. area. The building has six stories and is accessible for people with disabilities. There is a ramp from street level to entrance level, which is placed six steps above street level. There are revolving doors and separate doors for people in wheelchairs. The building is currently undergoing a renovation and the exercises were held in the old part of the building. The interior design of the building, in which part the exercises are held, consists of long hallways with offices and other rooms on each side. The primary vertical traffic is diverted by elevator whereas the horizontal traffic is distributed in hallways. The building is provided with emergency staircases in each corner of the building and in the middle section.

The exercises are initiated from a meeting room located on the fourth floor in one corner of the building. There is a large meeting table in the middle of the room with chairs around. The test subjects are seated around the table. The determined egress route is from the room with a right turn just after exiting the room into the hallway. The hallway is 106.5 meter long. The participants are supposed to make a left turn into another hallway after 53 meter . After 4 meters in the second hallway the participants have a fire exit to the emergency staircase on their left hand. Entering the emergency staircase the participants travel two floors of stairs to a safe place on the second floor. The stair is a two flight stair with intermediate landings. Each stair flight has ten steps and handrails in both sides. The handrail is only continuous on the inside. The building is not closed off for the experiment, and normal traffic might mix with the evacuation exercises.

The experiment is divided into five different phases. This is done to assess how different compositions of the test group influences evacuation parameters. In the first phase the participants walked one by one and on their own through the determined emergency route. All exercises were initiated by a local warning signal. The signal was only given in the room from where the exercises where initiated in order not to disturb the normal use of the building. This first phase is considered as the reference scenario, where the participants are walking unimpeded and with their own pace and is not influenced by others. In the second phase the participants were paired two and two. It was not a requirement that the pairs should stay together, but if they felt safe doing so it was their own choice. The third phase constituted groups of three. In the fourth phase the group where split in half and in the fifth and last phase everyone was evacuating at the same time. The five different phases are shown in table 1.

Table 1: Five different test phases.

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Single	Groups of 2	Groups of 3	Half	All

Each phase is only run one time since the exercises where scheduled to last only one afternoon the time frame did not allowed for any replication. Prior the exercises the participants were instructed in the determined emergency route and the alarm signal. Furthermore, the order in which the participants should respond to the local alarm signal is given beforehand. The local alarm signal sounds with a time interval of 30 to 90 seconds to notify the participants.

Data from the experiments are collected by recording each phase with temporarily fixed video cameras. The video footage is afterwards analyzed and the walking speeds horizontally and on stairs, densities and flow through doors are determined.

The focus of the study is the evacuation capability of blind people and people with low vision. It is likewise studied how they move individually and in groups in a simulated emergency situation.

Participants

The only requirement outlined for the participants to take part in this study is that they have low vision and is categorized as legally blind according to the American definition (Social Security Administation, 2006). Legally blindness can be translated into a visual acuity of a maximum of 20/200 measured in the best eye or having a visual field less than 20 degrees. Participants could use their usual assistive technology during the exercises no matter if it is a dog, a cane or anything else they prefer.

Participants are recruited from local networks, unions, and organizations with interest in safety for blind and visually impaired people. The recruitment process is initiated in August 2013. The goal is to reach around 20 participants, however the study can be completed with less participants.

The research team is not allowed to pay cash to the participants for their participation due to ethical regulation. However, all participants are given a symbolic gratitude in form of a $15 gift card to Starbucks as a Thank-You appreciation. In addition, all participants are invited to dinner at a local restaurant where their experiences during the exercises are discussed and the experiment is evaluated.

Prior the experiments all participants receive written information about the study and a consent form to review. Meetings with participants before the experiments are not possible and contact details to the research team are therefore provided for the participants to give them the option to ask any question they might have. The consent form provide information on the background for the study, procedure, benefit for participants and society as well as sections on liability. All participants are made aware that they take part on an entirely voluntary base and are informed that they can withdraw at any time. The consent form is provided electronically, in print with plain text and with large font, and in braille. At the day of the experiments each participant much sign the consent form. The responsible researcher goes through the consent form and provides further information on the project at the day of the experiment. It is a requirement to sign the consent form before participation is allowed.

Procedure

The participants are recruited in the period from August to September 2013. The experiments are carried out on the September 27th, 2013 and the program of the day is given below.

Program of the day

12:30-13:00	Arrival and registration of the participants. Assistance of participants to meeting room
13:00-13:45	Introduction and information on the experiments and the project. Signing and collection of informed consent forms
13:45-14:05	Instruction in the emergency route and guided tour

14:10-16:30	Evacuation exercises - Single movement - Movement in groups
17:00-19:30	Evaluation and Dinner at local Restaurant

The participants are met by a member of the research team at the entrance to the building. The research team member assist participants complete the security check and guide them to the meeting room, from which the experiment is initiated. The route used to get to the meeting room is not a part of the determined emergency route used in the experiments. At arrival to the meeting room each participant is registered and degree of visual impairment and special characteristics are noted.

After arrival all participants is given information about the experiments and the project. During the introduction participants are encouraged to ask all the questions they might have. Each participant hereafter signs the consent form. Members of the research team are assisting where necessary.

During the experiments members of the research team are assigned different positions along the determined emergency route. The research assistants are allowed to give verbal way finding guidance if need. Due to restriction in the building the participants are not allowed to use their own route and only the determined emergency route must be used. When the participant reaches the safe location on the second floor they are assisted back to the meeting room.

After the exercises the participants are transported to the nearby restaurant for the evaluation and dinner. Interview session with each participant is likewise scheduled. The content of the interview is to assess each participant's experience with the exercises and how they are using the public environment in terms of buildings they visit and difficulties they experience.

Data Collection

Collection of data is done by recording the exercises on video. Cameras are installed along the determined emergency route both in the corridors and in the staircase. There is used different mounting equipment based on the possible mounting options in the building. The cameras are positioned at the same day as the experiments are carried out. The mounting is completed in the morning. Chequered mats are filmed as a reference layer for the movie recordings in order to make measurements while extracting raw data from the recordings. The cameras used are of the type X170 Drift Innovation, manufactured by Drift Innovation, London, UK. These cameras are filming with a wide angle of 170 degrees and have a rotatable lens. The recordings are filmed with 30 frames per second which is the native format for the cameras. The cameras are placed to film from above directly downwards, and with an angle. The downwards position is primarily used to determine the person density whereas the angled position gives an overview to observe the interaction between the participants and their interaction with the environment. The different positioning options are shown in figure 1.

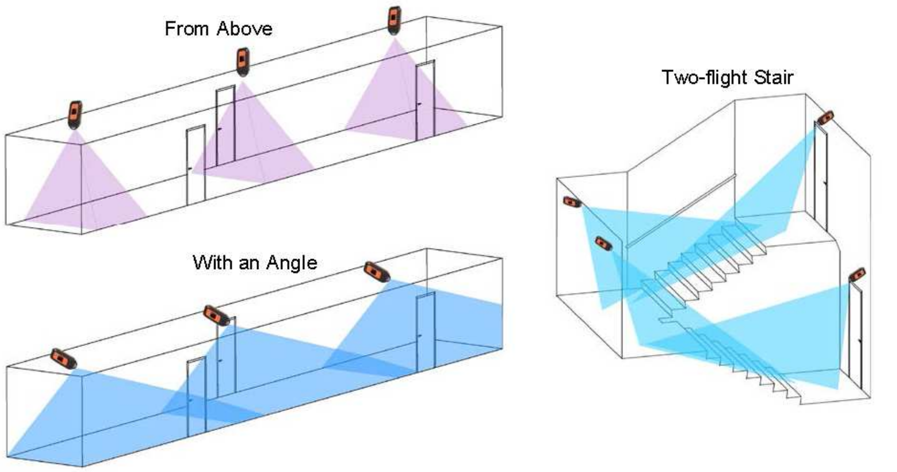

Figure 1: Camera Positioning.

A preliminary plan for the camera placement is shown in Figure 2. The floor is made of terrazzo and is provided with expansion joints for every approximately 5 meters. These joints are used as check points in the data analysis. The length of the corridor is 53 meters and there are 11 joints along that length. At each joint one camera is positioned filming from above and two cameras are filming with an angle pointing in opposite directions. Each phase of the experiments is recorded to separate files. Due to the internal distance between the cameras a stopwatch is used for synchronization. The synchronization process is repeated prior each phase of the experiment.

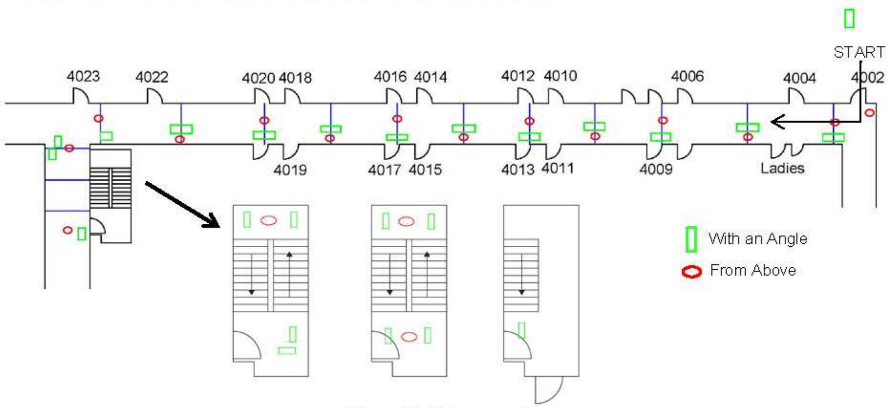

Figure 2: Initial camera plan

After the exercises the participants are asked to take part in an interview study revealing their experiences with the experiments. This study likewise entail an assessment of their use of the public environment including their visiting behavior of different building types and an examination of the difficulties experienced. This study is in addition conducted on a voluntary basis. The interview is based on a questionnaire consisting of three parts – identification, the experiment, and the public environment. The duration of the interview is estimated to 30 minutes and is recorded with a dictaphone.

All participants are guaranteed full anonymity during the evacuation experiments and in the interview study and all personal information are held confidential.

Tasks on the day of experiments
The research team consists of four members. The members are assigned different tasks throughout the day.

The identified tasks of the day are:

Task	**Responsible**
Mounting of Cameras	All members
Filming of chequered mat	Two members
Starting Cameras and Synchronize	Two members
Welcoming Participants at entrance level	One member – Research Responsible
Registration of participants	One member
Introduction to project and exercises	One member – Research Responsible
Initiation of evacuation exercises	One member
Observation during exercises	Three members
Assisting participants to original location	Two members
Demounting of equipment	Three members
Evaluation	One member – Research Responsible

Each member of the research team receives the following information regarding the experiment; synchronization procedure, scheme for registration of each participant, participant grouping for each experimental phase, camera plan, and a list of participants.

Ethical considerations

In Denmark there are two authorities to consult while performing scientific experiments involving human beings – The Danish Data Protection Agency and The National Committee on Health Research Ethics.

In the case where information on the participant's health conditions is a parameter in the experiment, it is, according to the law, mandatory to notify for the Danish Data Protection Agency. In this experiment information on the participants eventually impairments is recorded and can be used for identification and it is therefore considered as a health condition. The PhD project and the activities included herein are notified to the Agency and permission to data analysis is given. Regarding The National Committee on Health Research Ethics an informal description of the project is submitted and they have judged that these experiments do not need to be notified, because they are not considered as biomedical experiments or involve humane material. It is classified as an observation, interview and questionnaire survey which are not obligated to notification (Den Nationale Videnskabsetiske komité, 2012).

Even though the project does not need approval by an ethical committee the research team at The Technical University of Denmark, Department of Civil Engineering has developed an internal codex describing ethical procedures for evacuation experiments involving vulnerable people.
The internal codex prescribes that all participants in a simulated evacuation needs information about the project prior the evacuation. Dependent on the population all participants need to sign an informed consent to participate. Participant will receive both verbal and written information about the project. Participation in the experiments is on a voluntary basis and the participants are allowed to withdraw at any time. If a participant during the exercises feels uncomfortable or the like, it is possible to immediately withdraw from participation. All participants are guaranteed anonymity and none of the recorded material will be distributed to a third party.

It is expected that the participants will benefit from participation. The participants will experience how they react in a simulated evacuation, how they interact with other people around them and how the built environment affects their performance. Likewise it is expected that the experiments will benefit both science and society. The study will give scientific results that can contribute to models prescribing the evacuation behavior of people with visual impairments. The society will benefit due to an increased focus on vulnerable groups in our population and their right to be safe as everyone else.

Acknowledgement

The project is funded by Østifterne and they had made it possible to do this study outside Denmark and thereby contribute to expansion on international results for people with visual impairments.

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Appendix N

Questionnaire used in interviews

Questionnaire used for the interview after exercises on level one and two.

1. Gender

   ☐ Male

   ☐ Female

2. Age (e.g. in an interval of 5 years)

   ____

3. What is the severity of your visual impairment? How much are you able to see?

   ____

   ____

   ____

4. Degree of visual impairment (visual acuity)
   - ☐ Moderate visual impairment (0.25-0.125)
   - ☐ Severe visual impairment (0.1-0.05 or visual field 20) (Legal blindness)
   - ☐ Profound visual impairment (0.04-0.02 or VF 10 degree or less)
   - ☐ Near-blindness impairment (less than 0.02)
   - ☐ Total visual impairment (no light perception)
5. What is the origin of your visual impairment?
   - ☐ ______________________________
6. 6. Do you use any assistive technology? (e.g. crutches, walking stick, guiding dog)

   ____
7. Do you have other impairments beside your visual impairment?
   - ☐ Yes, what: ________________
   - ☐ No
8. Were you familiar with the inside of the building and its escape routes prior the exercises?
   - ☐ No
   - ☐ Yes, what is your relation to the building?:

   ____

   ____
9. For the following parts of the escape exercise, please assign the level of difficulty you experienced on a 5-point scale, where 5 is very difficult and 1 is very easy.
   - ☐ Recognize the alarm signal
   - ☐ Find the exit from the room
   - ☐ Walking in the corridor
   - ☐ Negotiate doors
   - ☐ Walk down the stairs
   - ☐ Find the safe place
   - ☐ Negotiate obstacles while walking

10. Did you need rest periods during the exercises?

   - ☐ No
   - ☐ Yes, how many and where:

     ____

     ____

11. Could you have benefited from receiving help during the exercises?

   - ☐ No
   - ☐ Yes, what type of help would you suggest:

     ____

     ____

12. How would you assess your own performance during the exercises on a 5-point scale, where 5 is a very good performance and 1 is a very bad performance?

   - ☐ 1
   - ☐ 2
   - ☐ 3
   - ☐ 4
   - ☐ 5

13. Please give an overall description of your experience with the exercises

     ____

     ____

     ____

     ____

14. Give 4 examples of buildings you visit in your everyday life besides your home. (e.g., metro stations, Concert Halls, Public buildings, restaurants, cafes, shopping malls, etc.)

   1. ______________________________
   2. ______________________________
   3. ______________________________
   4. ______________________________

15. How often do you visit the following buildings?

Building/Frequency	Daily	Weekly	Monthly	Annually
Building				
Building 1				
Building 2				
Building 3				
Building 4				
Shopping mall				
Transport Terminals				
One- family house				
Apartment building				
Theatre/concert				
Sport facility				
Restaurant/Cafe				

16. How do you move around in the following buildings?

Travelling/ Building	On your own	On your but using an assistive technology	Type of assistive technology	With an assistant
Building				
Building 1				
Building 2				
Building 3				
Building 4				
Shopping mall				
Transport Terminals				
One- family house				
Apartment building				
Theatre/-concert				
Sport facility				
Restaurant/-Cafe				

17. What barriers do you experience when visiting the following buildings? (doors, stairs, elevators, etc.)

Barrier/ Building	Doors	Stairs	Elevator/escalator	Width of corridor	Unexpected obstacles
Building 1					
Building 2					
Building 3					
Building 4					
Shopping mall					
Transport Terminals					
One- family house					
Apartment building					
Theatre/concert					
Sport facility					
Restaurant/-Cafe					

18. Do you think about your possibilities for escape when you visit unfamiliar buildings? (In case of fire or another emergency)

    ☐ Every time
    ☐ Often
    ☐ Rarely
    ☐ Never

19. Have you ever been informed about the evacuation procedure or emergency routes in a building you were not familiar with?

    ☐ Yes
    ☐ No

20. If yes, how did you get the information?

    ____

    ____

Thank you very much for your participation.

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Appendix O

Informed Consent - WDC

Type	Informed Consent Form
Title:	**Informed Consent - WDC**
Author:	J.G. Sørensen
Year:	2013

Evacuation of people with visual impairments

You are being asked to participate in a research study conducted by Janne Gress Sørensen, M.Sc. Civil Engineering, from the Technical University of Denmark at the Department of Civil Engineering. The research is a part of the PhD Study "Evacuation of people with visual impairments" and the results will contribute to the dissertation. You have been selected as a possible participant in this study because you have previously indicated that you have some degree of visual impairment. Please read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

PARTICIPATION AND WITHDRAWAL

Your participation in this study is completely voluntary. If you choose to be in this study, you may withdraw from it at any time without a penalty or consequences of any kind. The investigator may also remove you from this research if circumstances arise which warrant doing so.

PURPOSE OF THE STUDY

The purpose of the study is to identify evacuation characteristics of people who are blind and visually impaired. This will be done through a number of evacuation drills held in a natural environment as well as in unfamiliar places. The evacuation drills will be recorded with temporarily installed video cameras. The video footage will be analyzed with respect to different evacuation parameters including, but not limited to, walking speeds, staircases, person densities, density dependency and flow. In addition, the behavior of the test persons and the interaction between them and interactions with the environment will be investigated.

People with visual impairments are generally considered more vulnerable in case of an emergency than sighted people. It is known from previous studies that the more vulnerable parts of the population (i.e. children, elderly and people with disabilities) are more likely injury during emergencies. The data collected will be used to develop new evacuation models that specifically describe how blind and visually impaired people function during an evacuation. These models can then be used to help design more effective fire safety systems for buildings.

Fire safety design of today's buildings is mainly based on knowledge of able-bodied adults, and it is therefore questionable if this is a sufficient safety level for all building occupants. Little is known about evacuation characteristics of people who are blind or visually impaired. More information about this group is therefore needed.

We believe this study will help increase accessibility of commercial buildings for visually impaired workers. Increased accessibility has enabled a larger proportion of people to use the built environment. Therefore, it is of importance to equally consider people who are blind or have a visual impairment in designing the fire safety strategy within a building and thereby ensure equal egress. People with disabilities have the same rights to be safe in case of an emergency as everyone else.

The evacuation exercises will be held in an office building in the Washington D.C. area. The exercises will include movement through rooms, hallways and on stairs. Prior to the experiments, participants will receive instructions in the evacuation procedure. The exercises will be divided into different parts to measure different parameters. The exercises will include the movement of individuals, small groups and larger groups. The exercises will be initiated by a local alarm signal. The participants will be instructed about the signal beforehand.

PROCEDURES

If you volunteer to participate in this study, we will ask you to participate in the following activities:

1. Introduction to the project (10 min)
2. Question and answer session (30 min)
3. Collection of consent forms (10 min)
4. Introduction to the exercises and instructions (10 min)
5. Evacuation exercises (2 h)
    - Single evacuation
    - Group evacuation
6. Evaluation (30 min)
7. Interview session (individual) - optional

The evacuation exercises will be held on Friday, September 27, 2013. There will be provision of a free meal and drinks will be served. The optional interviews will be individual sessions with each participant. They will be conducted between September 28 and October 4, 2013 at a location agreed-upon with each participant. The interview session will cover each participant's experiences during the evacuation drills and use of the public environment. You may choose to participate only in the evacuation drill and not the interview session. However, we would like as many participants as possible to take part in the interview. The duration of an interview is approximately 30 minutes.

POTENTIAL BENEFITS

It is expected that you will benefit from the exercises through an increased knowledge of evacuation procedures in an unknown building. It is also expected that you will learn more about how you personally will react (physically and mentally) during an evacuation.

Results from the evacuation drills will benefit both science and society. These evacuation drills will create new knowledge on evacuation characteristics and behavior of people with visual impairments. The drills will provide information on walking speeds, characteristics related to stair usage, person density dependency and evacuation flows as well as human behavior. The information will help create a foundation for developing evacuation models for people who are blind and visually impaired. These models may serve as input for evacuation calculations to predict total evacuation times. It is expected that new models will be able to predict more realistic evacuation times and thereby possibly increase the level of safety for everyone.

PAYMENT FOR PARTICIPATION

Participants will not receive any payment for their participation, but will receive a $15 Gift Card for Starbucks as compensation. Participants will not receive the Gift Card if they decide to withdraw during the exercises or are withdrawn by the investigator.

CONFIDENTIALITY

All identifying information obtained in connection with this study will remain confidential and will only be disclosed with your permission or as required by law. Evacuation exercises will be videotaped with temporarily installed cameras. Interviews will be audiotaped. The video footage and interview recordings will be stored in a locked environment where only Researcher Sørensen and fire research team at the Department of Civil Engineering have access. Information will under no circumstances be distributed to any other party than the fire research group at the Technical University of Denmark.

The information will consist of research identification number, gender, age-interval and data on walking speeds and person densities. All participants are guaranteed anonymity, and cannot be identified based on published results. All data from the study will be destroyed within one year after the PhD is complete or by January 1, 2016, whichever comes first.

IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact Janne Gress Sørensen, DTU Civil Engineering, Brovej Building 118, DK-2800 Kongens Lyngby, +45 4525 1644 or 1-800-343-8890 (toll-free), jags(at) byg.dtu.dk.

POTENTIAL RISKS AND DISCOMFORTS

Participants will not be exposed to any fire hazards such as smoke, heat, flames or fire. However the exercises are associated with the following potential risks; 1) fatigue due to repeated exercises, 2) falling on stairs, 3) injury, 4) property damage. There may be other unknown risks.

Participants must be aware that participation in the study entails risks of injury. The description of these risks is not complete and unknown or unanticipated risks may result in injury or illness.

EXPRESS ASSUMPTION OF RISK AND RESPONSIBILITY

By voluntarily participating in this study you hereby knowingly and freely assume all such risks, both known and unknown, including full responsibility for and risk of bodily injury, death or property damage. The Technical University of Denmark is not able to offer financial compensation, nor to absorb the costs of medical treatment should you be injured as a result of participating in this study.

By agreeing to participate in this study, you verify that you are physically fit and sufficiently qualified, trained and capable to participate in the study. You assume full responsibility, for yourself, for any bodily injury, accident, illness, death, loss of personal property and expenses related thereto as a result of any accident which may occur while you participate in the study. You assume the risks of personal injury, accidents and/or illness, including but not limited to sprains, torn muscles and/or ligaments, fractured or broken bones, eye damage, cuts, wounds, scrapes, abrasions, contusions, dehydration, oxygen shortage (anoxia), exposure, head, neck, and spinal injuries, allergic reaction, shock, paralysis or death. By participating in this study, you agree to refrain from using alcohol or drugs prior to and during your participation in the study.

If you observe any unusual significant hazard during your participation in the study, you agree to remove yourself from participation and bring it to the attention of the investigator or the nearest staff member immediately. I will bring any and all injuries suffered by me to the immediate attention of the authorized representative of the Technical University of Denmark.

RELEASE AND COVENANT NOT TO SUE

I understand that the evacuation exercises will be held in an office building under the jurisdiction, custody and control of the U.S. General Services Administration, an agency of the United States (GSA).

I will use the highest degree of care and caution while on the premises and will walk and stand only where specifically permitted by the authorized representative of the Technical University of Denmark for the purposes set forth in this Consent To Participate In Research Study.

In confirmation of the foregoing, I hereby indemnify and hold harmless GSA and the Technical University of Denmark, their agents and employees, from and against any and all losses, claims, damages, expenses, and liability whatsoever (whether or not such liability has been judicially determined), including attorneys' fees, resulting from or in any manner attributable to my presence on or in the vicinity of the premises, except to the extent such loss, claim, damage, expense, or liability arises out of or relates to the wrongful acts or negligence of GSA or the Technical University of Denmark, or their agents or employees.

I will never institute any action or suit at law or in equity against GSA or the Technical University of Denmark, or both, their agents and employees, nor institute, prosecute or in any way aid in the institution or prosecution of any claim, demand, action, or cause of action for damages, costs, loss of services, expenses, or compensation for or on account of any damage, loss or injury, either to person or property, or both, resulting or arising out of my presence on or in the vicinity of the premises, unless the damage, loss or injury arises out of or relates to the wrongful acts or negligence of GSA or the Technical University of Denmark, or their agents or employees.

MISCELLANEOUS PROVISIONS

This Consent To Participate In Research Study may not be varied except in writing, and incorporates my entire understanding with respect to my participation in the research study and my presence on or in the vicinity of the premises.

This Consent To Participate In Research Study and the Release and Covenant Not To Sue will be binding upon my successors and assigns.

In the event any portion of this Consent To Participate In Research Study is deemed invalid for any reason, the balance of the Consent To Participate In Research Study will remain in full force and effect.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE:

I have read carefully the foregoing Consent To Participate In Research Study and I understand the content and procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form in an accessible format. (Please check all that apply)

- ☐ I give permission for the interview to be recorded.

____

Name of Subject

____

Name of Legal Representative (if applicable)

____________________________________ ____________

Signature of Subject or Legal Representative Date

SIGNATURE OF INVESTIGATOR:

In my judgment the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

____________________________________ ____________

Signature of Investigator Date

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The aim of this PhD study is to provide knowledge on evacuation, accounting for people with different impairments. An experimental program for data collection was developed. Evacuation parameters for heterogeneous populations, and homogenous population of able-bodied people and people with visual impairments were measured. It was found that the total evacuation time for a heterogeneous population was twice the time for a homogenous population of able-bodied adults. The experiments and corresponding results also revealed that theories for able-bodied adults cannot be applied for visually impaired persons.

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